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DESIGN AND CALIBRATION OF MICROWAVE ANTENNA GAIN STANDARDS

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ABSTRACT

A set of antenna gain-standard horns covering the microwave range from 0.77 cm to 31.5 cm has been designed and carefully calibrated. The horn fabrication is simple and can be duplicated accurately from the drawings supplied. A simple method of extending and improving the accuracy of Schelkunoff's gain curves is also described.

PROBLEM STATUS

This is a final report on this phase of the problem; work on the problem is continuing.

AUTHORIZATION

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DESIGN AND CALIBRATION OF MICROWAVE ANTENNA GAIN STANDARDS

INTRODUCTION

The need for accurate and practical microwave antenna gain standards has led to the design and calibration of a series of pyramidal horns covering the microwave bands from 0.77 cm to 31.5 cm. The series consists of eleven broadband horns having gains ranging from 24.7 db to 13.7 db. There is a horn for each waveguide size in the range. The horns can be easily and accurately duplicated from drawings supplied in this report.

DESIGN

Three requirements were considered of prime importance in the design: a useful gain figure, simplicity of construction, and accuracy of calibration. The fabricated type of horn (Fig. 1), with flat metal sheets forming the sides, was decided upon as the best means of satisfying the construction requirements. For simplicity, the horns were designed so that the E- and H-plane flares meet the waveguide in a common plane.

Another consideration was the over-all size and weight. It was impractical to scale the horns from one band to another throughout the range, since the horns at the longer wavelengths would be too large and those at the shorter wavelengths too small. Accordingly, there are five different designs; each of the other six horns was scaled from one of these.

The 8-mm and 1.8-cm horns were scaled from the 1.25-cm horn; the 4.75-cm horn from the 3.2-cm horn; the 3.95-cm and 6-cm horns from the 10-cm horn; and the 15-cm horn from the 23-cm horn. In scaling, the values of l_R had to be altered slightly in order to make a simple junction at the waveguide. This was necessary because, with one or two exceptions, the inside dimensions of the waveguides are not scaled from one band to another. The adjustment made only a very slight change in the calculated gain (about 0.02 to 0.03 db).

The 3.95-cm horn represents an overlapping of the 3.2-cm band and the 4.75-cm band. However, it was decided to include this horn in the series because it fits a standard waveguide size (1.250 x 0.625 in. O.D.) and it provided an opportunity to make experimental checks on the 10-cm horn from which it is scaled.

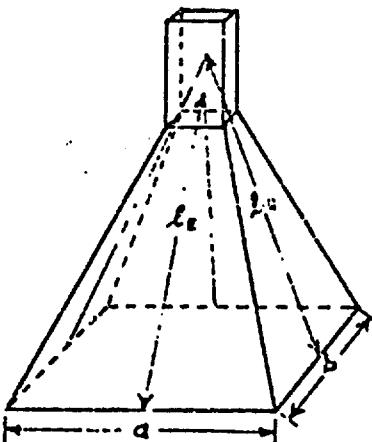


Fig. 1 - Physical dimensions
for calculating the gain

The basic design data including the dimensions, operating range, and design-point gain for all the horns are summarized in Table A-2.*

Readers who are interested in a detailed design procedure are referred to the Appendix, where a simple means of extending the range of Schelkunoff's gain curves and improving the accuracy of the gain figure obtainable from them is described. This method eliminates the necessity for long computations involving Fresnel Integrals, and yields very close agreement with the detailed calculations.

CONSTRUCTION

As mentioned previously, the fabricated type of horn using flat metal sheets was decided upon as most suitable. The one exception is the 8-mm design, where electro-forming was considered necessary because of the small size and close tolerances. Horns for the bands from 1.25 cm to 10 cm were made of brass sheets. At the 15-, 23-, and 30-cm bands, horns were fabricated from sheet aluminum using helium gas to facilitate welding the joints (heliarc process). This construction reduced the weight considerably and was found to be satisfactory for producing accurate, uniform, and rugged horns.

Dimensions for each set of horns are given in Figs. A-6 through A-17.

CALIBRATION

Experimental primary gain measurements (Fig. 2) were made in order to check the accuracy of the calculated gain.[†] Great care was taken in making these measurements. Both the horns and the bolometer detectors were carefully matched and the bolometer amplifier and output meter (VTVM) were calibrated accurately. The bolometer amplifier was found to be linear throughout the range used. The use of r-f coaxial cables was avoided because of instability, waveguide being used instead. Microwave absorbent material (1) was used to minimize reflections. Even so, difficulties were encountered at the longer wavelengths because of reflections and the large separation distances required. As Braun has shown (2), true Fraunhofer field conditions do not exist until a separation distance between horns of many times $2d^2/\lambda$ is attained, d being the larger aperture dimension. Because of these difficulties, experimental gain measurements at 10 cm and above were abandoned. It was decided to scale the 3.95-cm and 6-cm horns from the 10-cm horn in order to obtain reliable measurements at the shorter wavelengths. Figure 3 shows the anechoic test site. An example of the method used in evaluating the experimental data is given in the Appendix.

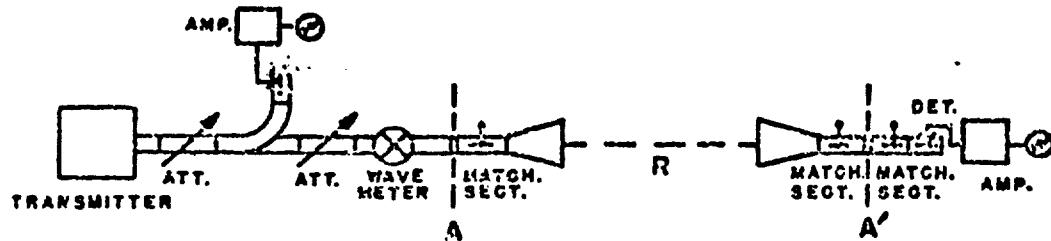


Fig. 2 - Experimental setup for gain measurements

*With the exception of Fig. A-1, all figures and tables bearing the letter A are grouped at the end of the Appendix, and are listed on page 6.

[†]For a general description of the methods used in making such measurements see Footnote 2, p. 7 of the Appendix, ref. pp. 582-585. The remarks in this reference about the minimum separation distance for the horns should be re-evaluated in the light of Ref. 2.

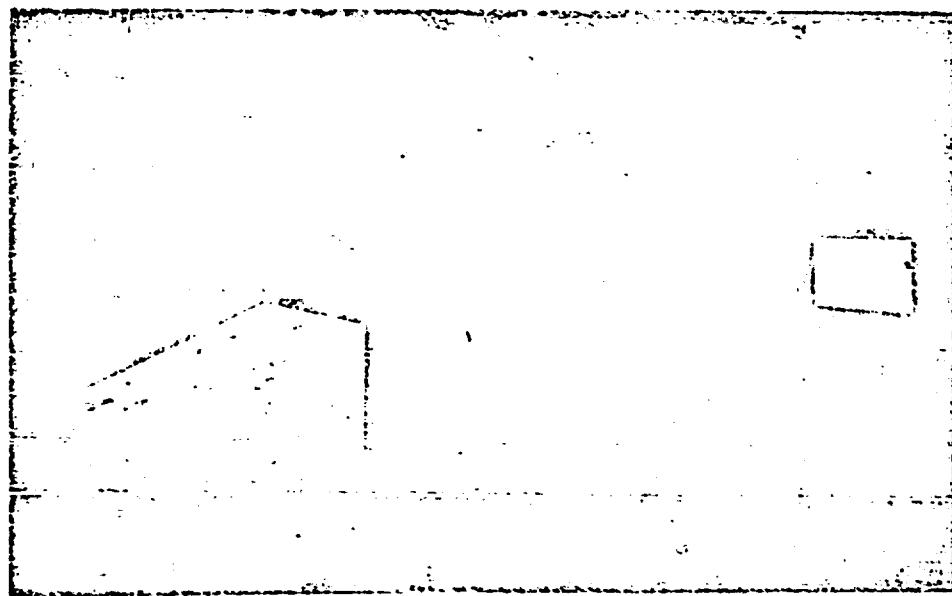


Fig. 3 - Anechoic test site

Measurements were made at several separation distances in each case, and were repeated many times, changing such variables as the power level and the peaking of the horns. See Figs. 3 and 4.

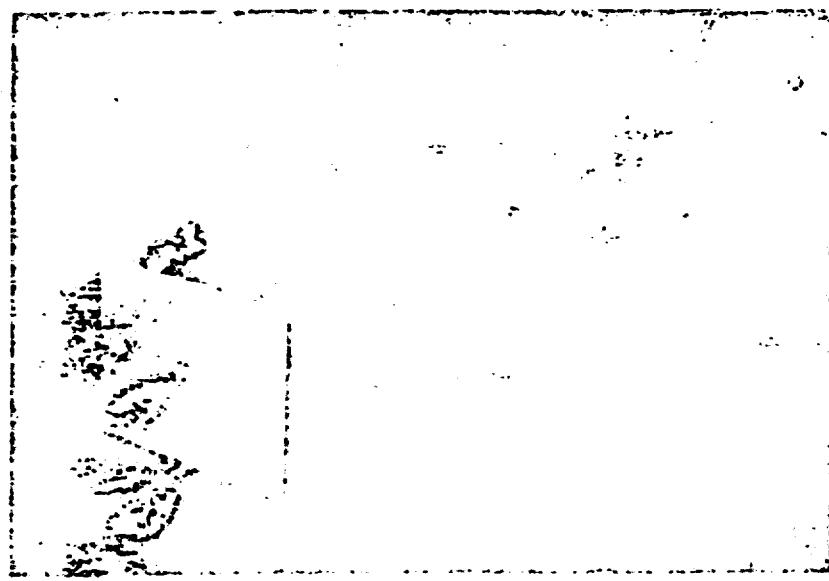


Fig. 4 - Horn and transmitter on adjustable mount

Gain curves for each band are shown in Fig. A-5 (a,b,c). Figures A-4 (a-f) show the field patterns for three basic horn designs.

REMARKS

Horns representing four basic designs were measured for mismatch over their bands. The greatest VSWR's encountered in the various bands are as follows:

<u>Band</u>	<u>Max. VSWR</u>
1.8 cm	1.10
3.2 cm	1.20
6 cm	1.25
23 cm	1.20

The horns for the other bands should have a VSWR close to that of the horns from which they were scaled.

In any event, when the horns are used in gain measurements, the VSWR should be measured at the wavelength used, and for accurate measurements the horns should be carefully matched, or allowance should be made for any mismatch. In either case the bolometer must be well-matched. The use of flange-to-flange connections rather than chokes, is recommended whenever operating at a wavelength differing from that for which the chokes were designed, since at some wavelengths choke-to-flange joints may introduce considerable mismatch.

ACCURACY

At any one wavelength the measured points showed a dispersion of less than 0.1 db. As a function of wavelength, the gain curve is not monotonic, as would be predicted from the theory, but shows small, though definite, periodic wiggles (see Fig. A-5 (b)). After exhaustive checking it is felt that these wiggles are actually present, and not due to experimental difficulties. This effect can probably be attributed to higher modes in the aperture and currents on the outside of the horn, both of which are neglected in the theory. However, since the wiggles are small, and since a tremendous amount of additional data would have to be taken to reproduce the wiggles accurately, a curve drawn through the average of the measured points was used. Taking into account all possible deviations from the true gain over each band, it was decided that the maximum possible error would be less than ± 0.9 db up to and including the 10-cm horns.

At wavelengths longer than 10 cm, where no direct experimental checks have been feasible, the gain has been calculated by means of Schelkunoff's formula. To arrive at a reasonable tolerance at these wavelengths, it was noted that below 10 cm the greatest discrepancy between the average measured gain (using Braun's correction curves² for near field effects) and the calculated gain at the same wavelength was of the order of 0.2 db. In general the difference was much less than this figure. Therefore it is felt that a tolerance of ± 0.5 db is reasonable for all horns above the 10-cm band. In all probability, the actual errors are considerably less than the maximum possible tolerances quoted.

ACKNOWLEDGMENTS

The author wishes to express his appreciation to E. H. Braun for his advice and cooperation and to F. W. Lashway for his suggestions in connection with the construction of the horns.

REFERENCES

1. Simmons, A. J., and Emerson, W. H., "An Anechoic Chamber Making Use of a New Broadband Absorbing Material," NRL Report 4193, 7 July 1953
2. Braun, E. H., "Gain of Electromagnetic Horns," Proc. I.R.E., Vol. 41, No. 1, pp. 109-115, Jan. 1953

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APPENDIX

Methods for Determining Horn Dimensions and Gain

BACKGROUND

Schelkunoff's gain curves in various forms^{1,2,3} were used for determining the tentative dimensions of the horns and for obtaining a first approximation to the gain. After the aperture dimensions had been chosen and a reasonable value for ℓ_E (the E-plane slant height) had been set, the H-plane slant height, ℓ_H , was uniquely determined by the requirement that the flared sides of the horn meet the waveguide in the same plane (Fig. 1, p. 1). For the purpose of calculating the expected gain, this value of ℓ_H was approximated by the relation

$$\ell_{H_{approx.}} = \frac{1 - \frac{w_E}{b}}{1 - \frac{w_H}{a}} \ell_E \quad (1)$$

where a = H-plane aperture dimension

b = E-plane aperture dimension

w_E = E-plane inside dimension of the waveguide

w_H = H-plane inside dimension of the waveguide.

After the tentative gain had been determined, the exact value of ℓ_H was obtained from the formula

$$\ell_H = \frac{a}{a - w_H} \sqrt{\left[\left(\ell_E\right)^2 - \left(\frac{b}{2}\right)^2\right] \left[\left(1 - \frac{w_E}{b}\right)^2\right] + \left[\frac{a - w_H}{2}\right]^2} \quad (2)$$

¹Schelkunoff, S. A., "Electromagnetic Waves," D. Van Nostrand, Inc., New York, pp. 363-365, 1943

²Silver, S., "Microwave Antenna Theory & Design," McGraw-Hill Book Co., Inc., New York, pp. 588-589, 1949

³Schelkunoff, S. A., and Friis, H. T., "Antennas - Theory and Practice," John Wiley and Sons, Inc., New York, pp. 528-529, 1952

In using Schelkunoff's gain curves, it was found that no one family of curves in the references mentioned covered a range great enough to include all the desired sizes of horns. Furthermore, certain parts of the curves were found to be less accurate than others. To overcome these difficulties a new procedure has been devised.⁴ A brief review of the relationship of the curves to the gain formula will help to clarify the procedure. The notation is substantially that used in the recent book by Schelkunoff and Fritts,³ and by Silver.²

The Schelkunoff curves give the directive gain for horns flared in either of the two principal planes; ϵ_E is the directive gain of a sectoral horn flared in the E-plane, and ϵ_H is the directive gain of a sectoral horn flared in the H-plane. The two sectoral gain curves are obtained from the following formulas, expressed in terms of the tabulated Fresnel integrals $C(x)$ and $S(x)$:

$$\frac{\lambda}{b} \epsilon_H = \frac{4\pi b^2}{\pi} \left[\left\{ C(u) - C(v) \right\}^2 + \left\{ S(u) - S(v) \right\}^2 \right] \quad (3)$$

$$\frac{\lambda}{a} \epsilon_E = \frac{54 b^2}{\pi a} \left[C^2(w) + S^2(w) \right], \quad (4)$$

where

$$u = \frac{1}{\sqrt{2}} \left(\frac{\sqrt{\lambda b_H}}{a} + \frac{a}{\sqrt{\lambda b_H}} \right)$$

$$v = \frac{1}{\sqrt{2}} \left(\frac{\sqrt{\lambda b_H}}{a} - \frac{a}{\sqrt{\lambda b_H}} \right)$$

$$w = \frac{b}{\sqrt{2}\lambda b_E}$$

λ = wavelength.

The gain of a pyramidal horn is

$$g = \frac{8\pi b_E b_H}{ab} \left[C^2(w) + S^2(w) \right] \left[\left\{ C(u) - C(v) \right\}^2 + \left\{ S(u) - S(v) \right\}^2 \right]$$

This result can easily be obtained from the two sectoral curves by multiplying together $(\lambda/a)\epsilon_E$ and $(\lambda/b)\epsilon_H$, and dividing the result by $32/\pi = 10.1859$, yielding the convenient formula

$$g = \frac{\left(\frac{\lambda}{a} \epsilon_E \right) \left(\frac{\lambda}{b} \epsilon_H \right)}{\frac{32}{\pi}} \quad (5)$$

where $\frac{\lambda}{a} \epsilon_E$ and $\frac{\lambda}{b} \epsilon_H$ are read directly from the curves.

⁴Braun, E. H., "Calculation of the Gain of Small Horns," Proc. I.R.E., Vol. 41, No. 12, pp. 1785-6, Dec. 1953

EXTENSION AND APPLICATION

Braun's method⁴ provides a convenient means of extending the range of the gain curves and eliminating the inaccuracy arising from interpolations between curves. He introduces the arbitrary factors k_E and k_H to create a fictitious horn having these dimensions:

$$\begin{aligned} a &= k_H A, \quad l_H = k_H^2 L_H \\ b &= k_E B, \quad l_E = k_E^2 L_E \end{aligned}$$

where A , B , L_E , and L_H are the actual horn dimensions. By choosing the proper value for k_E and k_H , one can make l_E and l_H fall exactly on one of the respective gain curves for each plane. After the gain of the fictitious horn ($\kappa_{\text{fict.}}$) is read from the curves, the gain of the actual horn ($\kappa_{\text{act.}}$) is obtained from the relation

$$\kappa_{\text{act.}} = \frac{\kappa_{\text{fict.}}}{k_E k_H}$$

Since both k_E and k_H are arbitrary, one gain curve for each plane is all that is necessary. The Schelkunoff curves for $l_E = 50\lambda$ and $l_H = 50\lambda$ are convenient for this purpose and have been accurately recomputed and plotted on an expanded scale in Figs. A-2 (a,b) and A-3 (a,b) so that they may be read with such accuracy that it is no longer necessary to make the detailed calculations involved in using the gain formula. The curves were plotted from formulas (3) and (4). The values obtained from these formulas are tabulated in Table A-1. For maximum accuracy these values may be preferable to those obtained from the curves. Linear interpolation between points will yield good inaccuracy. The table makes it possible to plot any desired portions of the curves on whatever scale is preferred.

An example will demonstrate the simplicity of the method.

Actual horn: $A = 8.13\lambda$, $L_H = 19.72\lambda$

$B = 6.67\lambda$, $L_E = 18.52\lambda$

If it is desired to make use of the 50λ curves referred to above, the k 's are chosen as follows:

$$k_E^2 = \frac{50\lambda}{18.52\lambda} = 2.6998, \quad k_E = 1.643,$$

$$k_H^2 = \frac{50\lambda}{19.72\lambda} = 2.5355, \quad k_H = 1.592.$$

Fictitious horn: $b = k_E B = 10.96\lambda$, $l_E = 50\lambda$,

$a = k_H A = 12.94\lambda$, $l_H = 50\lambda$.

From the 50λ gain curves

$$\frac{\lambda}{a} \kappa_E = 80.77$$

$$\frac{\lambda}{b} \kappa_H = 98.92.$$

From formula (5),

$$R_{fict.} = \frac{\left(\frac{\lambda}{a} k_E\right) \left(\frac{\lambda}{b} k_H\right)}{\frac{32}{\pi}} = 784.40$$

$$g_{act.} = \frac{R_{fict.}}{k_E k_H} = 299.88, \text{ or } 24.77 \text{ db.}$$

Detailed calculations using the Fresnel integrals in the gain formula resulted in the same gain figure, 24.77 db. Similar comparisons at each of the other bands showed agreement within 0.01 db.

USE OF CORRECTION CURVES

The procedure for determining the true Fraunhofer gain from the primary gain test data, using Braun's near field correction curves, Fig. A-1 (a,b), is shown in the following example taken from actual measurements:

X-band horn dimensions: $a = 7.654$ in., $\ell_E = 13.484$ in.

$b = 5.669$ in., $\ell_H = 12.598$ in.

$\lambda = 3.20$ cm = 1.2598 in.

R (distance between horns) = 140.25 in.

$$\frac{4\pi R}{\lambda} = \frac{(12.598)(140.25)}{1.2598} = 1398.9.$$

$$\text{From test data } \frac{P_T}{P_R} = \frac{11.3}{0.123} = 91.87; \quad \sqrt{\frac{P_T}{P_R}} = 9.585$$

where P_T represents power transmitted and P_R power received.

$$\text{Gain}_{\text{uncorrected}} = \frac{\frac{4\pi R}{\lambda}}{\sqrt{\frac{P_T}{P_R}}} = \frac{1398.9}{9.585} = 145.95, \text{ or } 21.64 \text{ db.}$$

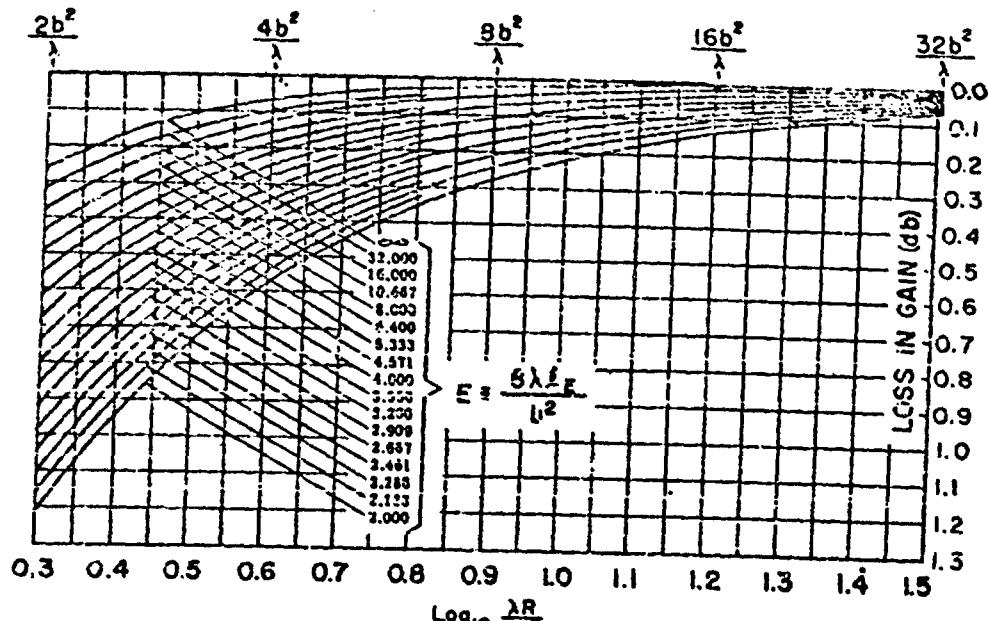
Parameters for using the correction curves:

E-plane:

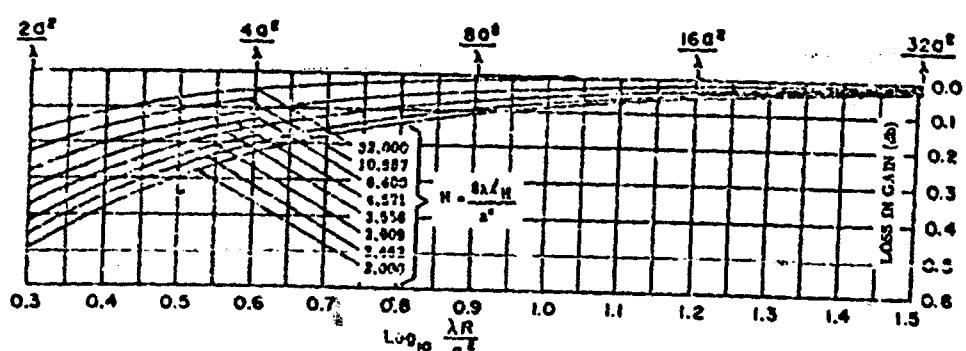
$$\frac{8\ell_E}{b^2} = \frac{(8)(12.598)}{32.13} = 3.1360$$

$$E = \left(\frac{8\ell_E}{b^2} \right) \quad \lambda : (3.1360)(1.2598) \approx 3.951 \quad \left. \right\}$$

$$\log \frac{\lambda R}{b^2} = \log \frac{(1.2598)(140.25)}{32.13} = \log 5.498 \approx 0.740 \quad \left. \right\}$$



(a) E-plane



(b) H-plane

Fig. A-1 - Braun's E- and H-plane correction curves

H-plane:

$$\frac{8l_H}{a^2} = \frac{(8)(13.484)}{58.584} = 1.8413$$

$$H = \left(\frac{3l_H}{a^2} \right) \lambda = (1.8413)(1.2598) = 2.320$$

$$\log \frac{\Lambda^R}{a^2} = \log \frac{(1.2598)(140.25)}{58.584} = \log 3.016 = 0.479$$

Reading from the correction curves:

E-plane correction	0.22 db
H-plane correction	0.38 db
Total correction	0.50 db
Uncorrected gain (above)	21.64 db
Corrected gain	22.14 db

The calculated gain, using Schelkunoff's formula, in this case was the same: 22.14 db.

DETERMINATION OF AN OPTIMUM HORN WITH SPECIFIED GAIN AND EQUAL BEAMWIDTHS

A simple means has been devised for finding the dimensions of a horn which satisfies the following requirements:

- (1) Specified gain
- (2) Optimum horn*
- (3) Equal beamwidths at the half-power points.

Although this can be done empirically, a set of factors was determined from Schelkunoff's gain formula, which yield the required horn parameters as a function of the absolute gain, g , alone.[†] These are as follows:

*An optimum horn is one for which the aperture dimensions have been chosen to give maximum gain when the slant heights are held fixed. This is the case when $a^2 \geq 3.18\lambda l_y$ and $b^2 \geq 2.08\lambda l_x$.

†This has been worked out by E. H. Braun in an unpublished report.

$$\frac{a}{\lambda} = 0.4675 \quad \sqrt{\epsilon}$$

$$\frac{b}{\lambda} = 0.3463 \quad \sqrt{\epsilon}$$

$$\frac{l_x}{\lambda} = 0.05764 \quad \epsilon$$

$$\frac{l_H}{\lambda} = 0.06885 \quad \epsilon$$

where a , b , l_x , and l_H are the usual parameters as defined (p.7).

A horn having these dimensions will have exactly the desired theoretical gain, and will be exactly an optimum horn. However, it should be pointed out that where a simple joint between the flared horn and the waveguide is desired, the value of l_H must be modified to make the horn fit the guide. This will change the gain by a small amount, usually a few tenths of a db, since the horn will no longer be exactly optimum. If a discrepancy of this magnitude is not important, l_H can be calculated to fit the waveguide exactly, using formula (2).

When a closer approach to the specified gain is desired, a slight change in the procedure is necessary. This is accomplished by the following steps:

- (1) Compute tentative parameters a' , b' , and l_x' in the same way as a , b , and l_x were computed above.
- (2) Obtain the approximate value, l_H' , to fit the waveguide, using formula (1), p. 7.
- (3) Calculate the tentative gain, ϵ' , by the method outlined on p. 9 using the primed parameters.
- (4) Recompute a , b , and l_x , substituting ϵ^2/ϵ' for ϵ .
- (5) Obtain the exact value of l_H from formula (2)
- (6) Recalculate the gain for the new parameters.

Since the theoretical gain is obtained very accurately in step 6, it is easy to determine the discrepancy between the desired gain and that now resulting from the adjustment to fit the waveguide.

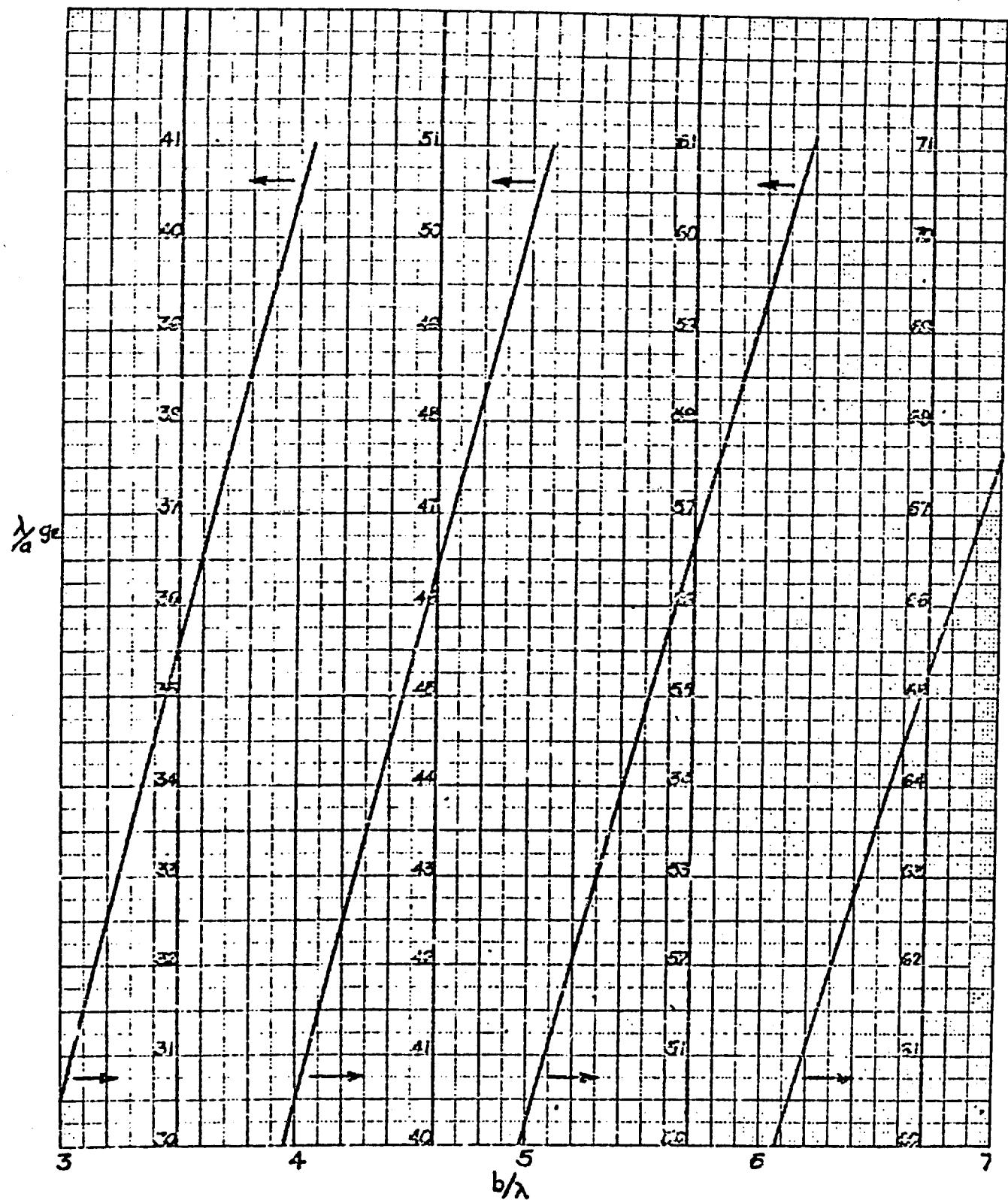


Fig. A-2 (a) Expanded E-plane theoretical gain curve

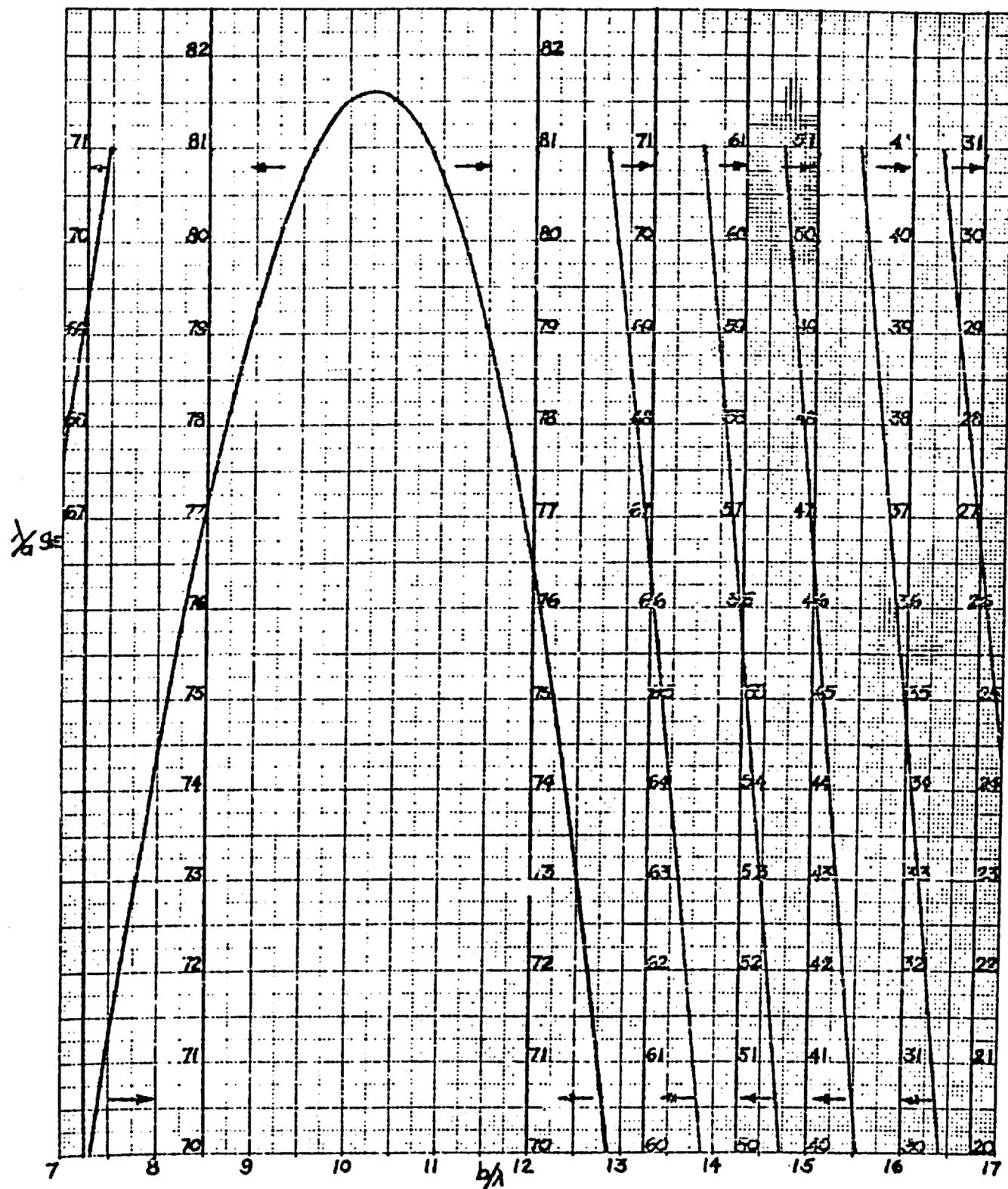


Fig. A-2 (b). Expanded E-plane theoretical gain curve

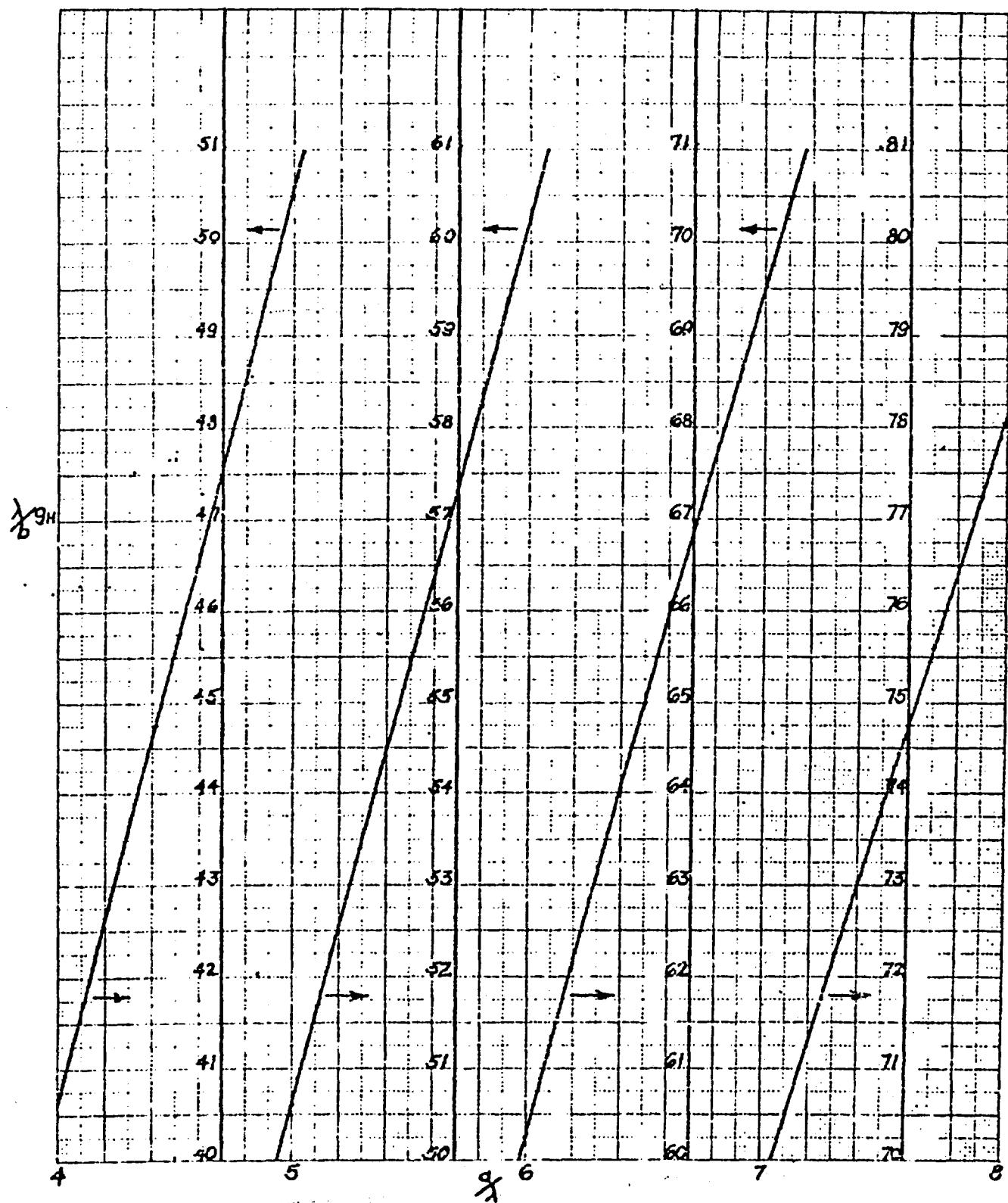


Fig. A-3 (a). Expanded H-plane theoretical gain curve

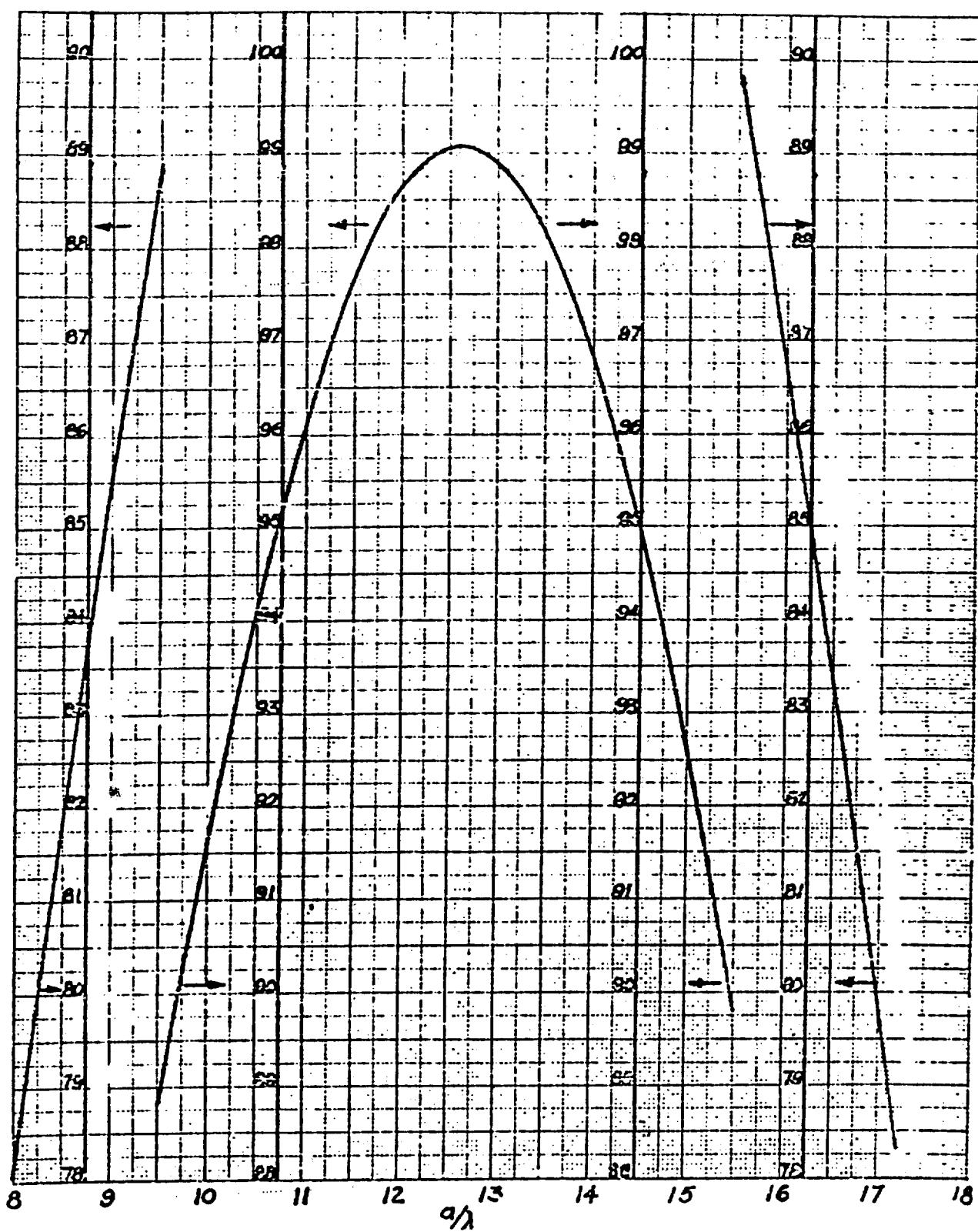
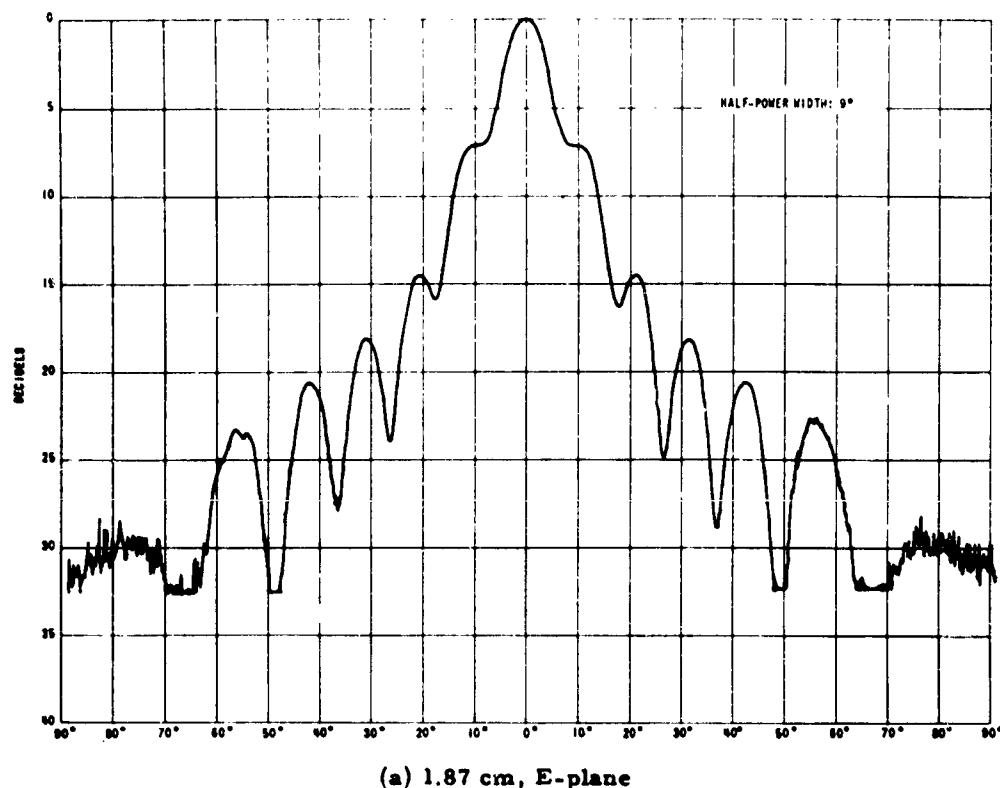


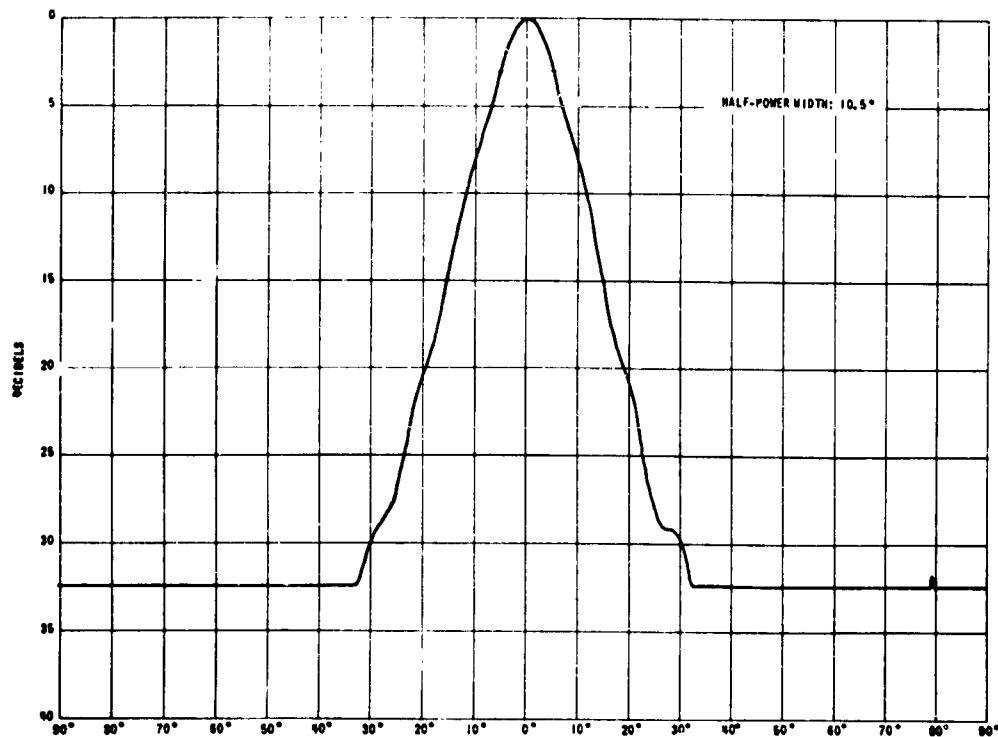
Fig. A-3 (b). Expanded H-plane theoretical gain curve

TABLE A-1
Data for Theoretical Gain Curves

(a) E-Plane ($L_E = 50\lambda$)											
b	$\frac{\lambda}{a} g_Z$	b	$\frac{\lambda}{a} g_E$	b	$\frac{\lambda}{a} g_E$	b	$\frac{\lambda}{a} g_E$	b	$\frac{\lambda}{a} g_E$	b	$\frac{\lambda}{a} g_E$
2.0	20.362	4.6	46.397	7.2	69.123	9.8	81.301	12.4	73.784	15.0	46.499
2.1	21.381	4.7	47.362	7.3	69.847	9.9	81.426	12.5	73.041	15.1	45.268
2.2	22.395	4.8	48.326	7.4	70.555	10.0	81.518	12.6	72.265	15.2	44.040
2.3	23.410	4.9	49.233	7.5	71.248	10.1	81.581	12.7	71.452	15.3	42.813
2.4	24.425	5.0	50.233	7.6	71.923	10.2	81.611	12.8	70.621	15.4	41.593
2.5	25.440	5.1	51.181	7.7	72.586	10.3	81.609	12.9	69.753	15.5	40.379
2.6	26.456	5.2	52.123	7.8	73.219	10.4	81.575	13.0	68.656	15.6	39.174
2.7	27.472	5.3	53.057	7.9	73.841	10.5	81.510	13.1	67.931	15.7	37.982
2.8	28.481	5.4	53.985	8.0	74.441	10.6	81.408	13.2	66.980	15.8	36.801
2.9	29.490	5.5	54.908	8.1	75.025	10.7	81.277	13.3	65.091	15.9	35.636
3.0	30.503	5.6	55.821	8.2	75.585	10.8	81.110	13.4	64.997	16.0	34.488
3.1	31.511	5.7	56.729	8.3	76.127	10.9	80.999	13.5	63.959	15.1	33.359
3.2	32.518	5.8	57.626	8.4	76.645	11.0	80.876	13.6	62.917	16.2	32.250
3.3	33.527	5.9	58.517	8.5	77.142	11.1	80.405	13.7	61.844	16.3	31.164
3.4	34.530	6.0	59.401	8.6	77.616	11.2	80.104	13.8	60.748	16.4	30.104
3.5	35.534	6.1	60.272	8.7	78.065	11.3	79.765	13.9	59.635	16.5	29.069
3.6	36.534	6.2	61.134	8.8	78.492	11.4	79.393	14.0	58.501	16.6	28.063
3.7	37.531	6.3	61.987	8.9	78.892	11.5	78.987	14.1	57.351	16.7	27.086
3.8	38.530	6.4	62.828	9.0	79.269	11.6	78.545	14.2	56.188	16.8	26.142
3.9	39.524	6.5	63.659	9.1	79.619	11.7	78.068	14.3	55.008	16.9	25.232
4.0	40.515	6.6	64.477	9.2	79.944	11.8	77.559	14.4	53.816	17.0	24.355
4.1	41.504	6.7	65.285	9.3	80.240	11.9	77.014	14.5	52.614	17.1	23.515
4.2	42.490	6.8	66.080	9.4	80.510	12.0	76.435	14.6	51.402	17.2	22.713
4.3	43.472	6.9	66.862	9.5	80.752	12.1	75.822	14.7	50.183	17.3	21.951
4.4	44.450	7.0	67.630	9.6	80.964	12.2	75.176	14.8	48.959	17.4	21.228
4.5	45.425	7.1	68.385	9.7	81.146	12.3	74.497	14.9	47.731	17.5	20.548
(b) H-Plane ($L_H = 50\lambda$)											
a	$\frac{\lambda}{b} g_H$	a	$\frac{\lambda}{b} g_H$	a	$\frac{\lambda}{b} g_H$	a	$\frac{\lambda}{b} g_H$	a	$\frac{\lambda}{b} g_H$	a	$\frac{\lambda}{b} g_H$
2.0	20.370	4.6	46.635	7.2	71.291	9.8	90.533	12.4	99.019	15.0	92.591
2.1	21.387	4.7	47.628	7.3	72.164	9.9	91.195	12.5	99.052	15.1	92.066
2.2	22.402	4.8	48.619	7.4	73.031	10.0	91.740	12.6	99.062	15.2	91.523
2.3	23.422	4.9	49.609	7.5	73.889	10.1	92.270	12.7	99.051	15.3	90.972
2.4	24.439	5.0	50.595	7.6	74.739	10.2	92.781	12.8	99.012	15.4	90.400
2.5	25.452	5.1	51.578	7.7	75.580	10.3	93.274	12.9	98.253	15.5	89.822
2.6	26.471	5.2	52.559	7.8	76.413	10.4	93.751	13.0	98.871	15.6	89.214
2.7	27.488	5.3	53.536	7.9	77.236	10.5	94.208	13.1	98.763	15.7	88.601
2.8	28.501	5.4	54.512	8.0	78.049	10.6	94.646	13.2	98.638	15.8	87.976
2.9	29.518	5.5	55.475	8.1	78.854	10.7	95.067	13.3	98.486	15.9	87.337
3.0	30.532	5.6	56.449	8.2	79.644	10.8	95.470	13.4	98.309	16.0	86.688
3.1	31.545	5.7	57.418	8.3	80.427	10.9	95.848	13.5	98.114	16.1	86.026
3.2	32.560	5.8	58.377	8.4	81.196	11.0	96.207	13.6	97.894	16.2	85.355
3.3	33.573	5.9	59.334	8.5	81.956	11.1	96.547	13.7	97.654	16.3	84.677
3.4	34.579	6.0	60.265	8.6	82.703	11.2	96.869	13.8	97.387	16.4	83.990
3.5	35.595	6.1	61.232	8.7	83.440	11.3	97.168	13.9	97.101	16.5	83.319
3.6	36.595	6.2	62.176	8.8	84.164	11.4	97.445	14.0	95.793	16.6	82.594
3.7	37.612	6.3	63.115	8.9	84.875	11.5	97.702	14.1	96.464	16.7	81.838
3.8	38.622	6.4	64.046	9.0	85.567	11.6	97.938	14.2	96.113	16.8	81.179
3.9	39.629	6.5	64.975	9.1	86.250	11.7	98.149	14.3	95.740	16.9	80.461
4.0	40.633	6.6	65.896	9.2	86.923	11.8	98.342	14.4	95.348	17.0	79.742
4.1	41.637	6.7	66.810	9.3	87.579	11.9	98.510	14.5	94.936	17.1	79.023
4.2	42.645	6.8	67.720	9.4	88.221	12.0	98.658	14.6	94.504	17.2	78.301
4.3	43.639	6.9	68.623	9.5	88.844	12.1	98.783	14.7	94.054	17.3	77.578
4.4	44.641	7.0	69.518	9.6	89.450	12.2	98.882	14.8	93.565	17.4	76.854
4.5	45.639	7.1	70.407	9.7	90.053	12.3	98.965	14.9	93.095	17.5	76.134

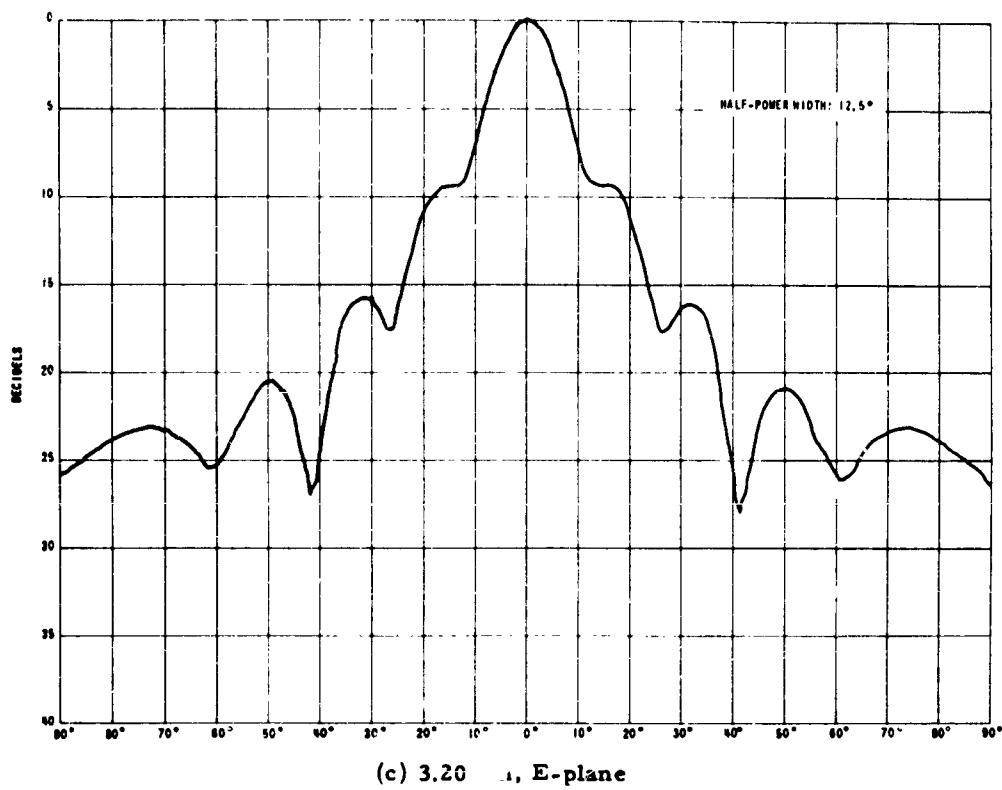


(a) 1.87 cm, E-plane

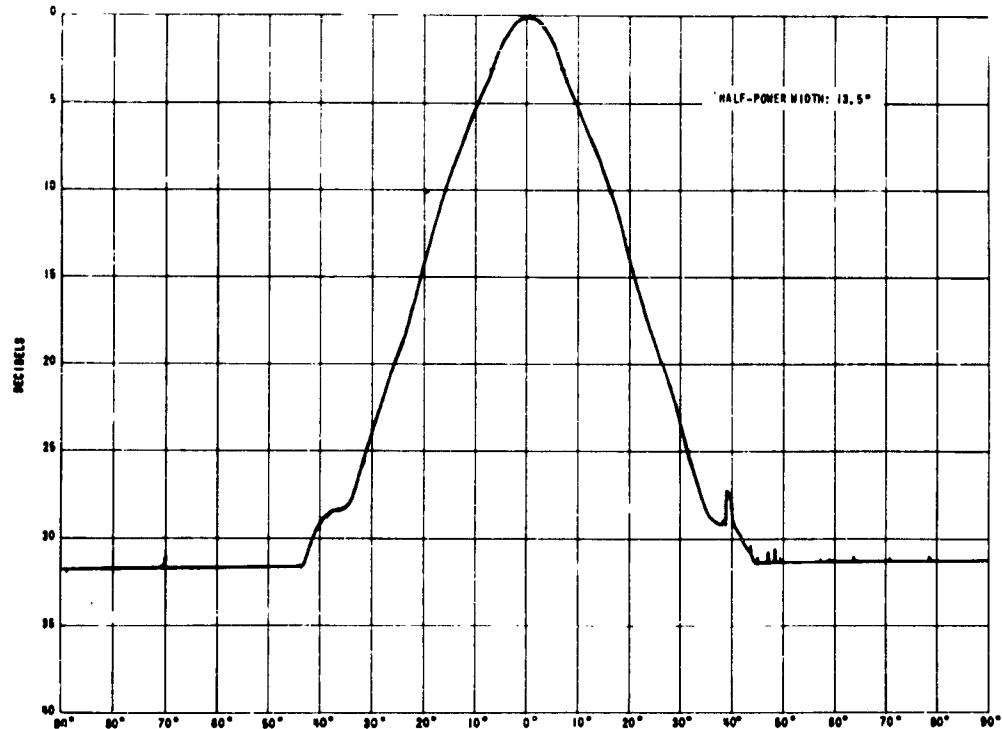


(b) 1.87 cm, H-plane

Fig. A-4. E- and H-plane field patterns

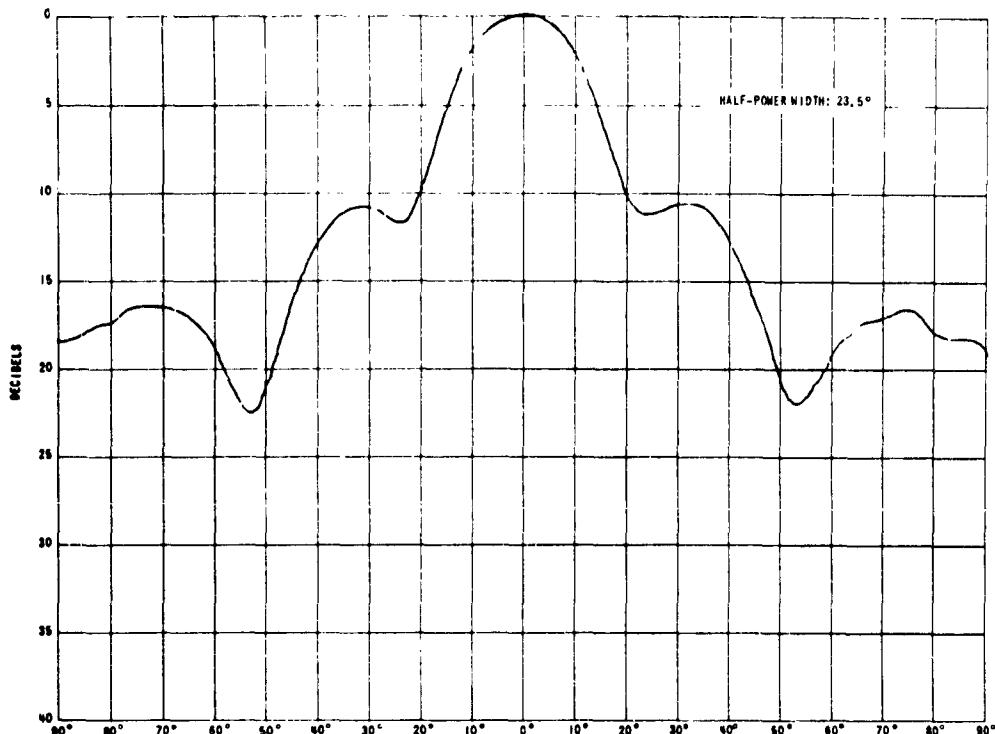


(c) 3.20 cm, E-plane

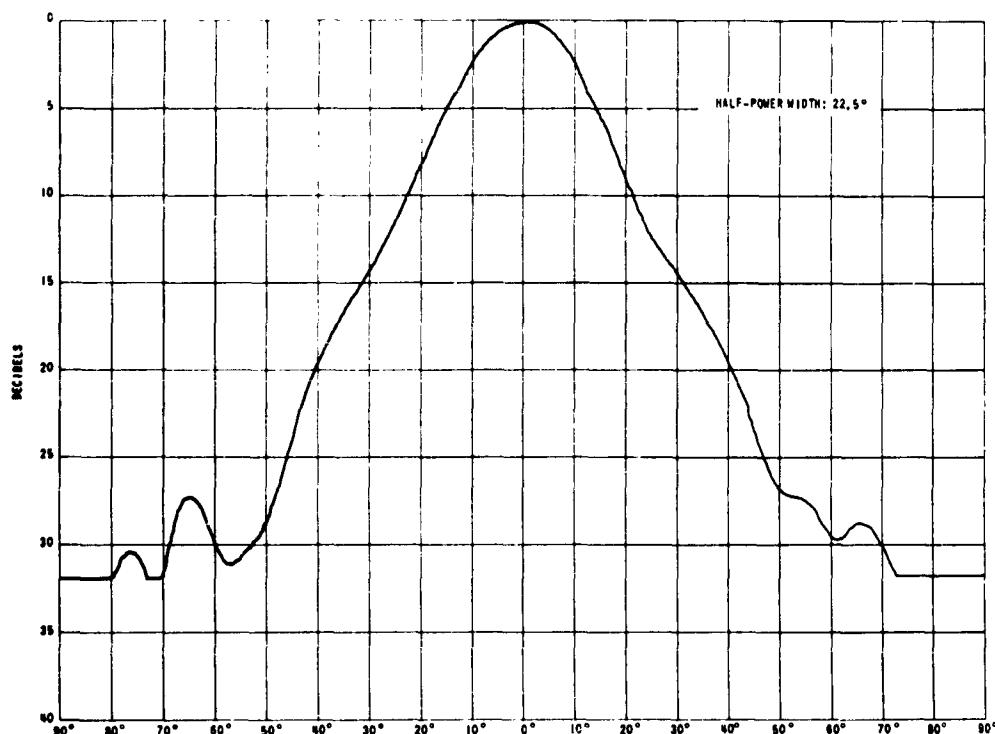


(d) 3.20 cm, H-plane

Fig. A-4. E- and H-plane field patterns



(e) 6.67 cm, E-plane



(f) 6.67 cm, H-plane

Fig. A-4. E- and H-plane field patterns

TABLE A-2
Summary of Gain-Standard Horn Data

Band	Frequency Range	Dimensions (I.D.) (in.)		Design- Point Frequency	Gain at Design Point (db)
{ 8 mm	0.77 - 1.13 cm	a = 2.720	b = 2.231	0.85 cm	24.7
	26,550 - 38,960 Mc	$\ell_H = 6.513$	$\ell_E = 6.197$	35,290 Mc	
{ 1.25 cm	1.13 - 1.66 cm	a = 4.000	b = 3.281	1.25 cm	24.7
	18,070 - 26,550 Mc	$\ell_H = 9.706$	$\ell_E = 9.113$	24,000 Mc	
{ 1.8 cm	1.66 - 2.42 cm	a = 5.984	b = 4.908	1.87 cm	24.7
	12,400 - 18,070 Mc	$\ell_H = 14.333$	$\ell_E = 13.633$	16,040 Mc	
{ 3.2 cm	2.42 - 3.70 cm	a = 7.654	b = 5.669	3.20 cm	22.1
	8100 - 12,400 Mc	$\ell_H = 13.484$	$\ell_E = 12.598$	9375 Mc	
{ 4.75 cm	3.60 - 5.20 cm	a = 11.360	b = 8.415	4.75 cm	22.1
	5770 - 8330 Mc	$\ell_H = 20.014$	$\ell_E = 18.700$	6315 Mc	
{ 3.95 cm	3.00 - 4.30 cm	a = 5.041	b = 3.733	3.95 cm	18.0
	6980 - 10,000 Mc	$\ell_H = 7.447$	$\ell_E = 6.555$	7595 Mc	
{ 6 cm	5.10 - 7.60 cm	a = 8.507	b = 6.300	6.67 cm	18.0
	3950 - 5880 Mc	$\ell_H = 12.462$	$\ell_E = 11.062$	4500 Mc	
{ 10 cm	7.60 - 11.5 cm	a = 12.760	b = 9.450	10.00 cm	18.0
	2600 - 3950 Mc	$\ell_H = 18.682$	$\ell_E = 16.593$	3000 Mc	
{ 15 cm	11.5 - 17.6 cm	a = 14.508	b = 10.747	15.22 cm	15.5
	1700 - 2600 Mc	$\ell_H = 16.508$	$\ell_E = 14.107$	1970 Mc	
{ 23 cm	17.6 - 26.5 cm	a = 21.931	b = 16.245	23.00 cm	15.5
	1130 - 1700 Mc	$\ell_H = 24.955$	$\ell_E = 21.325$	1300 Mc	
30 cm	26.0 - 31.5 cm	a = 21.931	b = 16.245	30.00 cm	13.7
	950 - 1150 Mc	$\ell_H = 28.730$	$\ell_E = 24.000$	1000 Mc	

Horns in brackets are scaled versions of each other, except for the ℓ_H dimensions, which are chosen to make a simple butt-joint at the waveguide

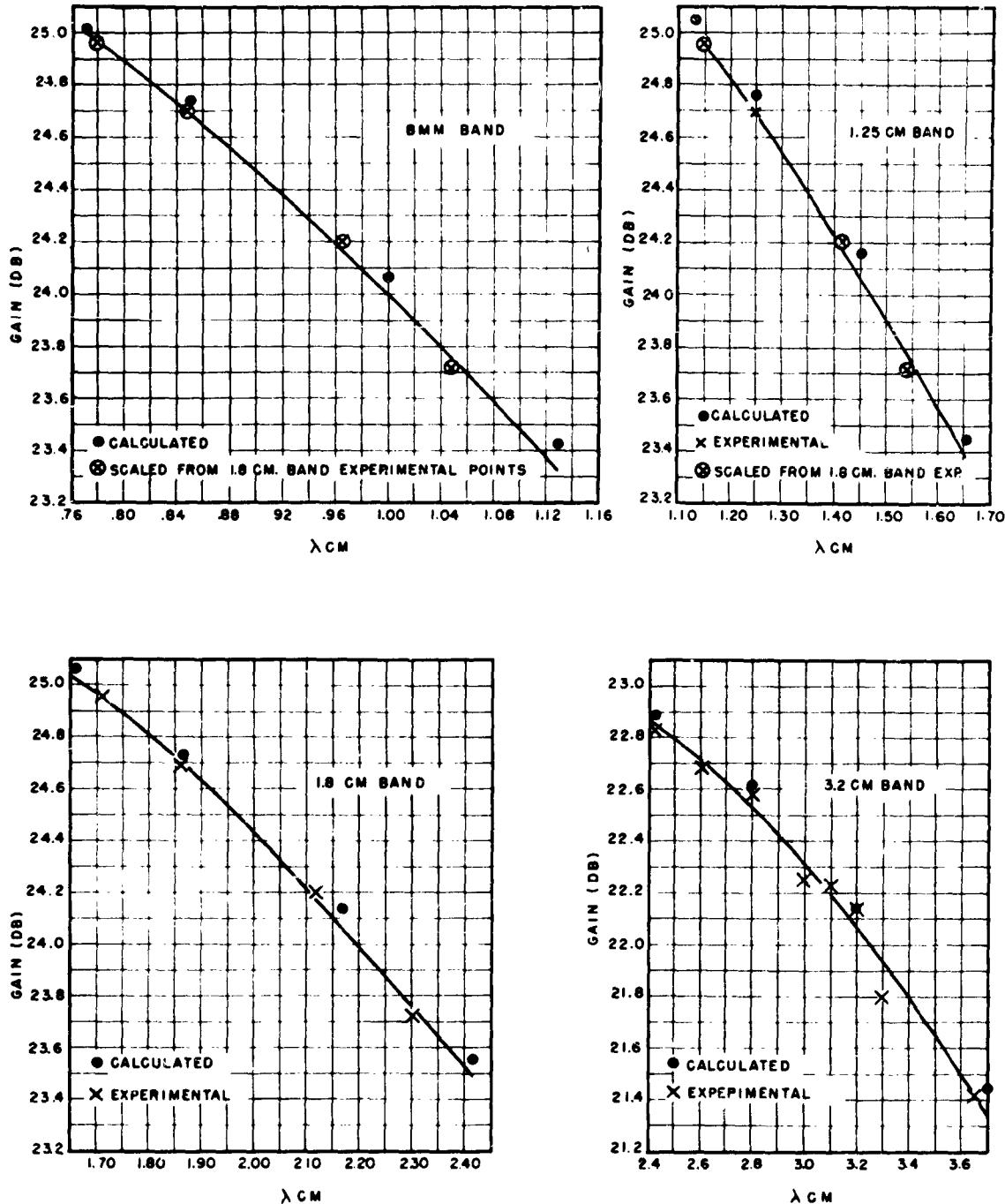


Fig. A-5 (a). Gain curves

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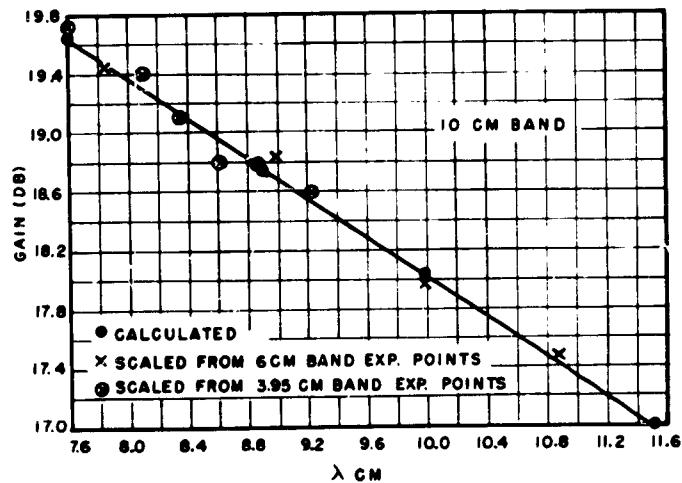
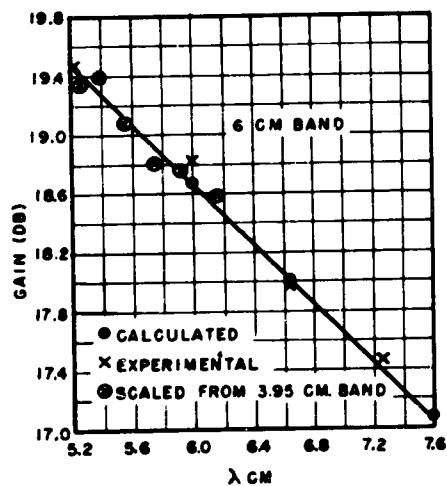
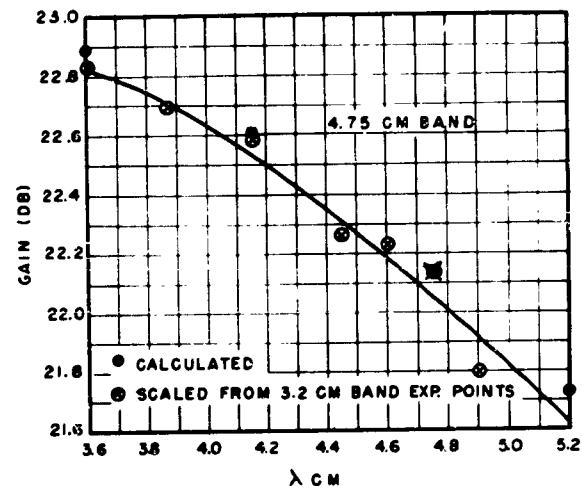
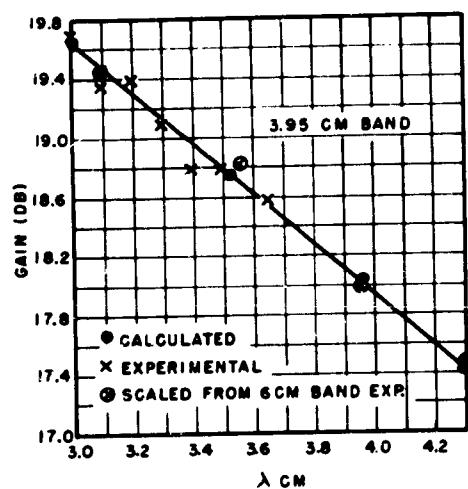
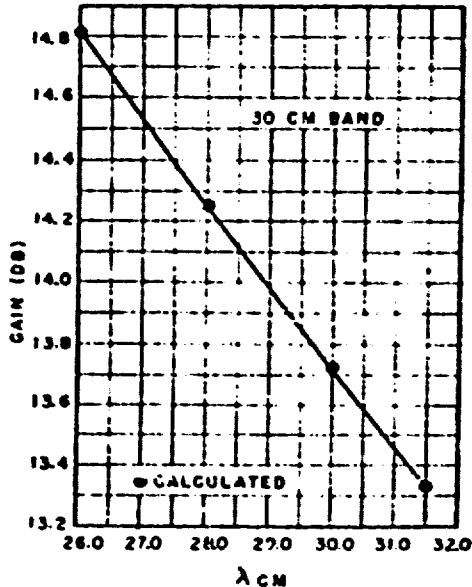
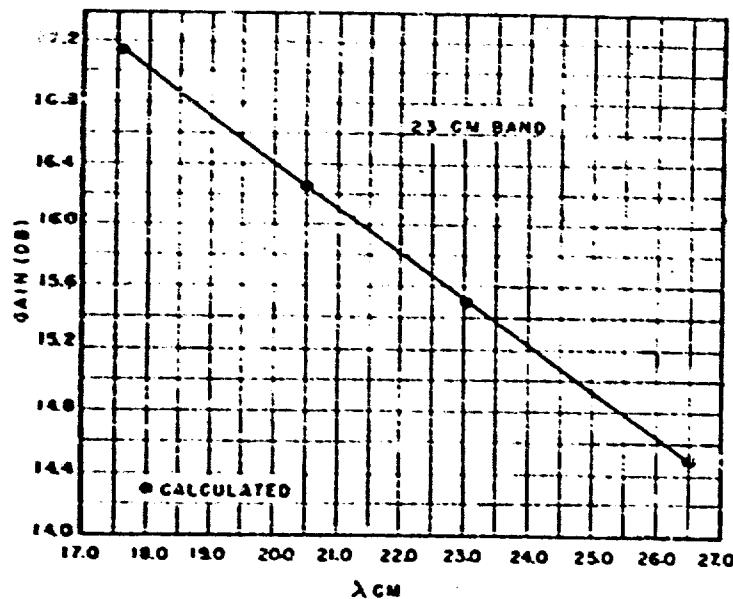
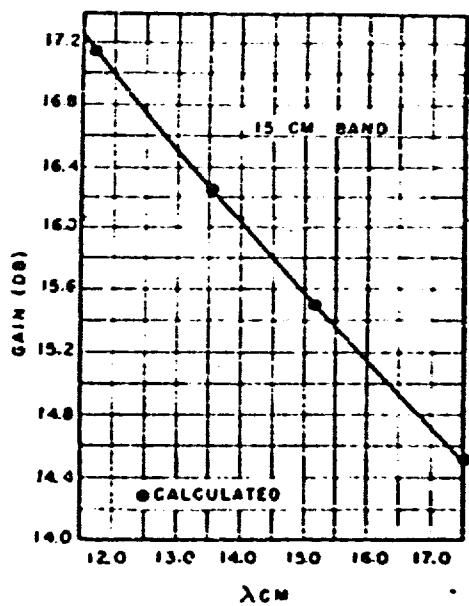


Fig. A-5 (b). Gain curves



CONVERSION CHART

ν (MHz)	λ (cm)						
2700-10.00	2800-10.71	2600-9.52	6400-4.59	6200-3.86			
2150-28.57	2250-10.53	1650-9.43	6250-4.65	6250-3.64			
1800-27.27	2900-10.38	8700-8.38	6500-4.62	8300-3.61			
1150-26.03	2950-10.17	8750-8.32	6550-4.58	8350-3.59			
1200-25.00	3000-10.00	8800-8.25	6600-4.55	8400-3.57			
1250-24.00	3050-9.84	8950-8.19	6650-4.51	8450-3.55			
1300-23.38	3100-9.78	8900-8.12	6700-4.48	8500-3.53			
1350-22.42	3150-9.72	8950-8.06	6750-4.44	8550-3.51			
1400-21.49	3200-9.66	9000-8.00	6800-4.41	8600-3.49			
1450-20.69	3250-9.61	9050-8.94	6850-4.38	8650-3.47			
1500-20.00	3300-9.56	9100-8.88	6900-4.35	8700-3.45			
1550-19.35	3350-9.51	9150-8.83	6950-4.32	8750-3.43			
1600-19.75	3400-9.47	9200-8.77	7000-4.29	8800-3.41			
1650-19.18	3450-9.40	9250-8.71	7050-4.26	8850-3.39			
1700-17.83	3500-9.37	9300-8.66	7100-4.23	8900-3.37			
1750-17.14	3550-9.35	9350-8.61	7150-4.20	8950-3.35			
1800-16.47	3600-9.33	9400-8.56	7200-4.17	9000-3.33			
1850-16.22	3650-9.32	9450-8.53	7250-4.14	9050-3.31			
1900-15.79	3700-9.31	9500-8.48	7300-4.11	9100-3.30			
1950-15.38	3750-9.30	9550-8.44	7350-4.08	9150-3.28			
2000-15.00	3800-9.29	9600-8.40	7400-4.05	9200-3.26			
2050-14.63	3850-9.29	9650-8.33	7450-4.03	9250-3.24			
2100-14.29	3900-9.26	9700-8.26	7500-4.00	9300-3.23			
2150-13.95	3950-9.22	9750-8.22	7550-3.97	9350-3.21			
2200-13.63	4000-9.19	5800-8.17	7600-3.95	9400-3.19			
2250-13.33	4050-9.18	5850-8.13	7650-3.92	9450-3.17			
2300-13.04	4100-9.12	5900-8.08	7700-3.90	9500-3.16			
2350-12.77	4150-9.13	5950-8.03	7750-3.87	9550-3.14			
2400-12.50	4200-9.18	6000-8.00	7800-3.85	9600-3.13			
2450-12.23	4250-9.18	6050-8.00	7850-3.82	9650-3.11			
2500-12.00	4300-9.19	6100-8.02	7900-3.80	9700-3.09			
2550-11.79	4350-9.19	6150-8.08	7950-3.77	9750-3.08			
2600-11.58	4400-9.12	6200-8.04	8000-3.75	9800-3.06			
2650-11.37	4450-9.14	6250-8.00	8050-3.73	9850-3.05			
2700-11.17	4500-9.07	6300-8.06	8100-3.70	9900-3.03			
2750-10.97	4550-9.09	6350-8.12	8150-3.63	9950-3.02			
				10000-3.00			

Fig. A-5(c). Gain curves and conversion chart

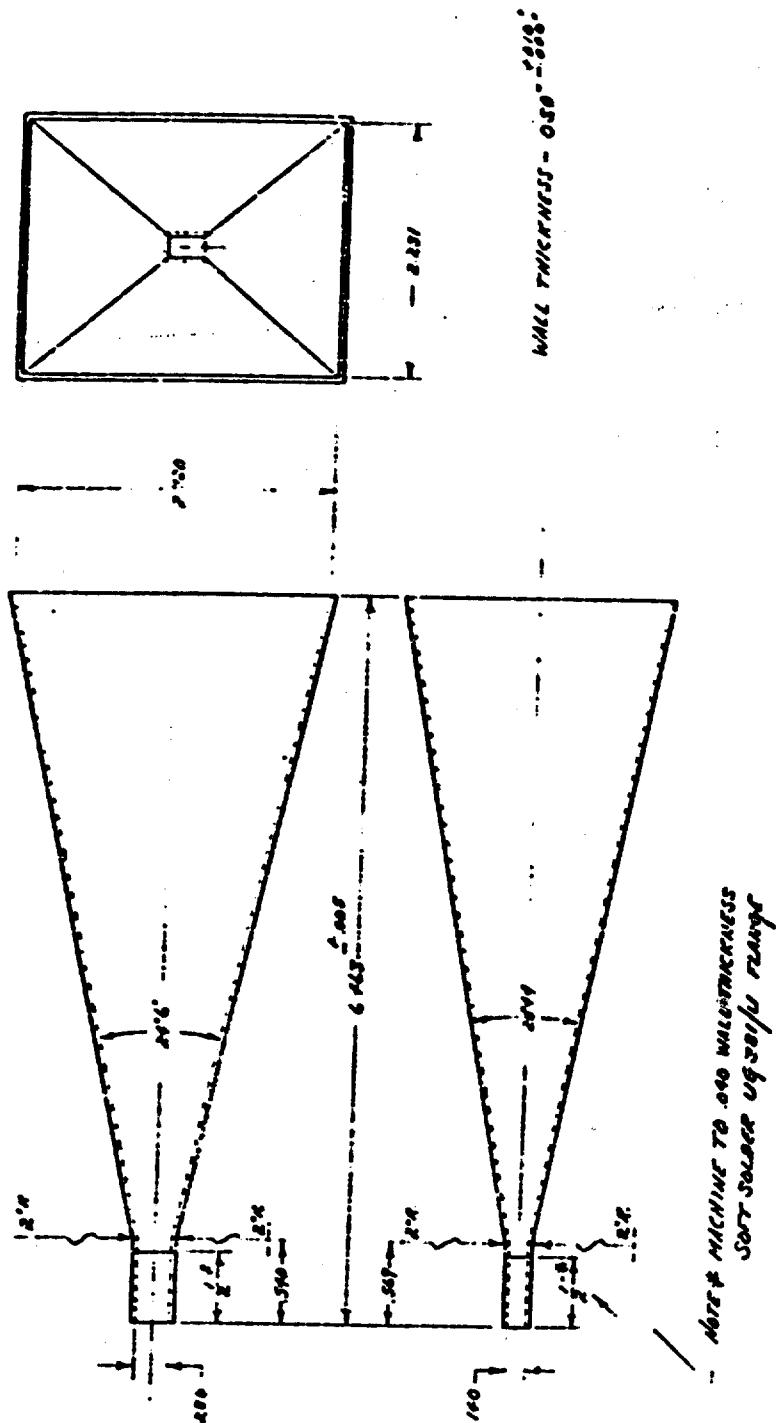


Fig. A-6. Electroformed horn. 8-mm-band gain-standard (0.77-1.13 cm)

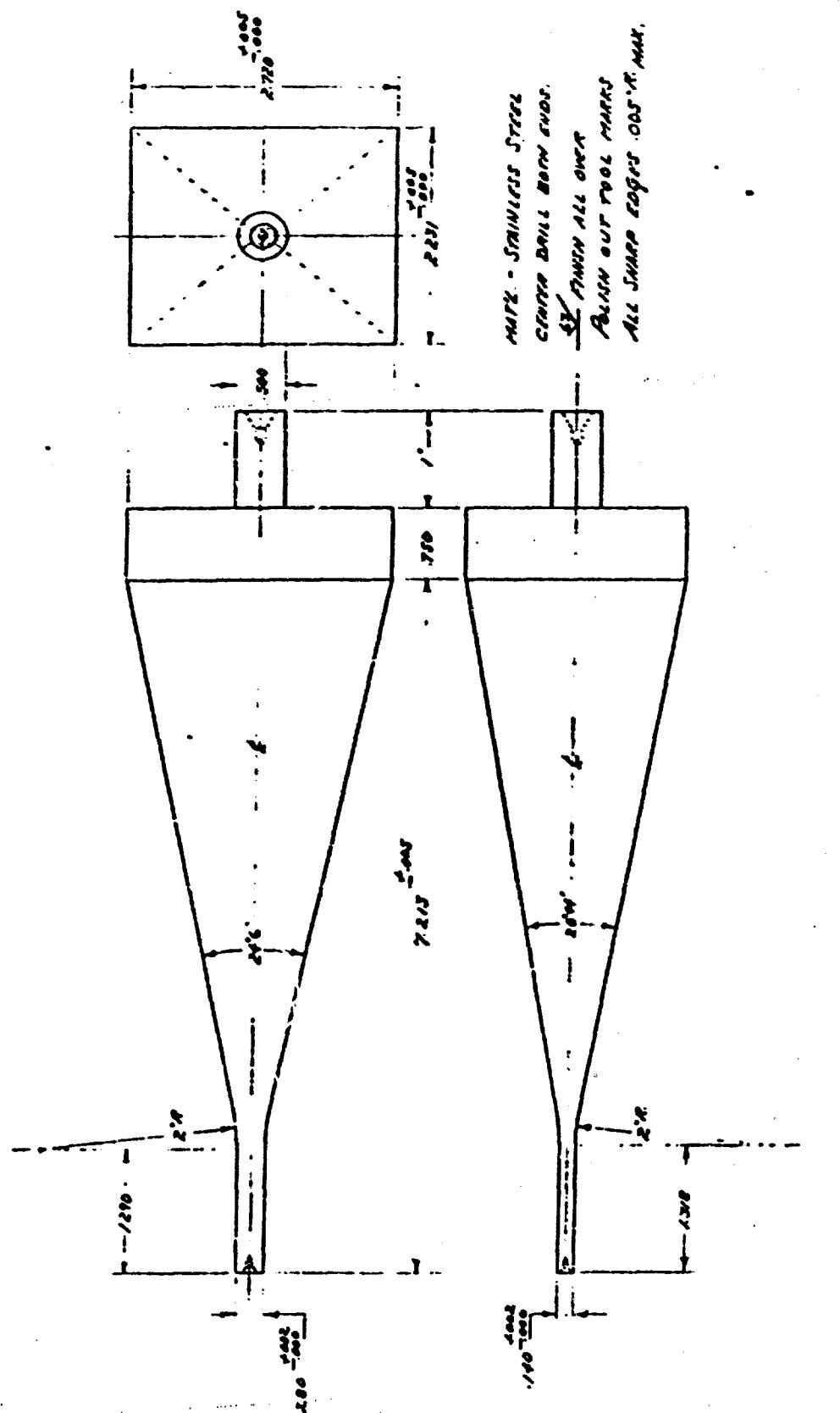


Fig. A-7. Mandrel for electroforming 8-mm-band gain-standard horn

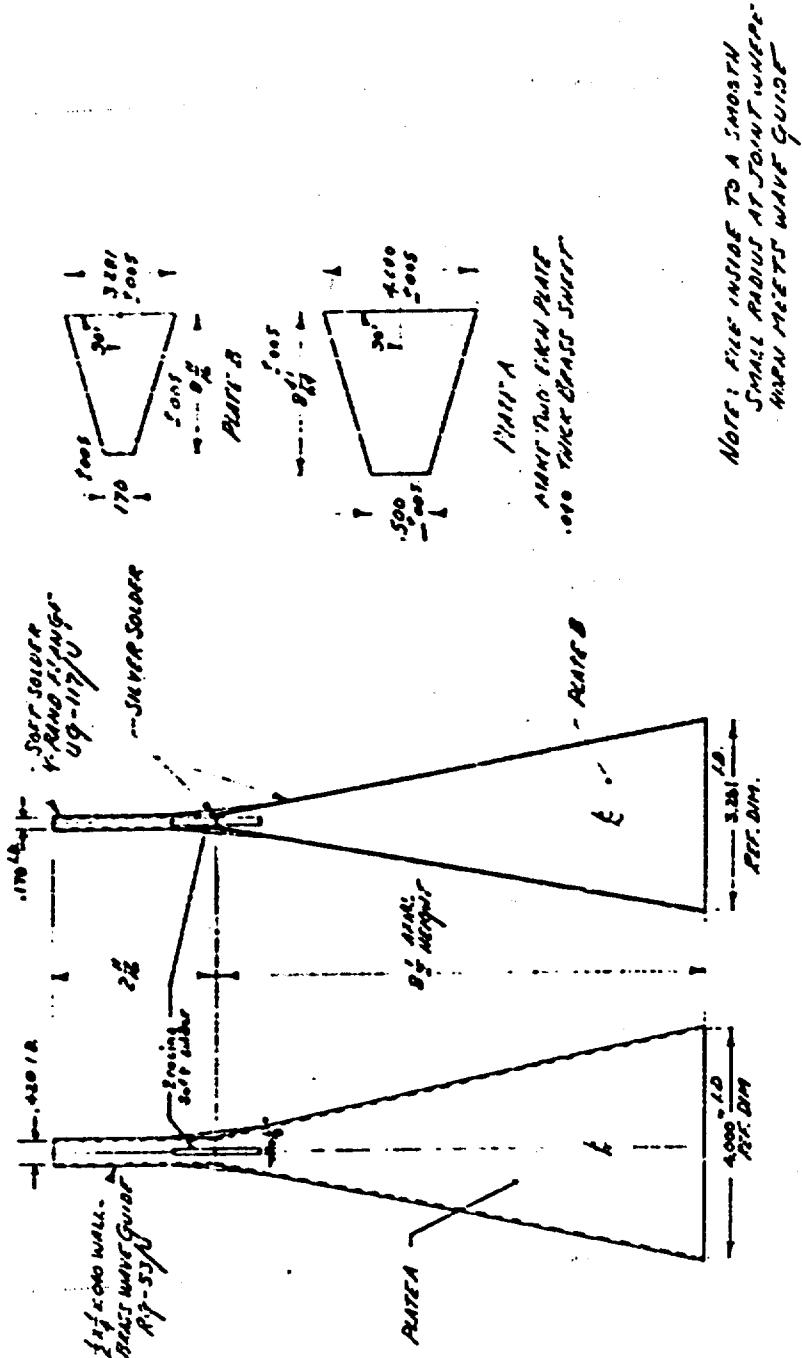


Fig. A-8. 1.25-cm-band gain-standard horn (1.13-1.66 cm)

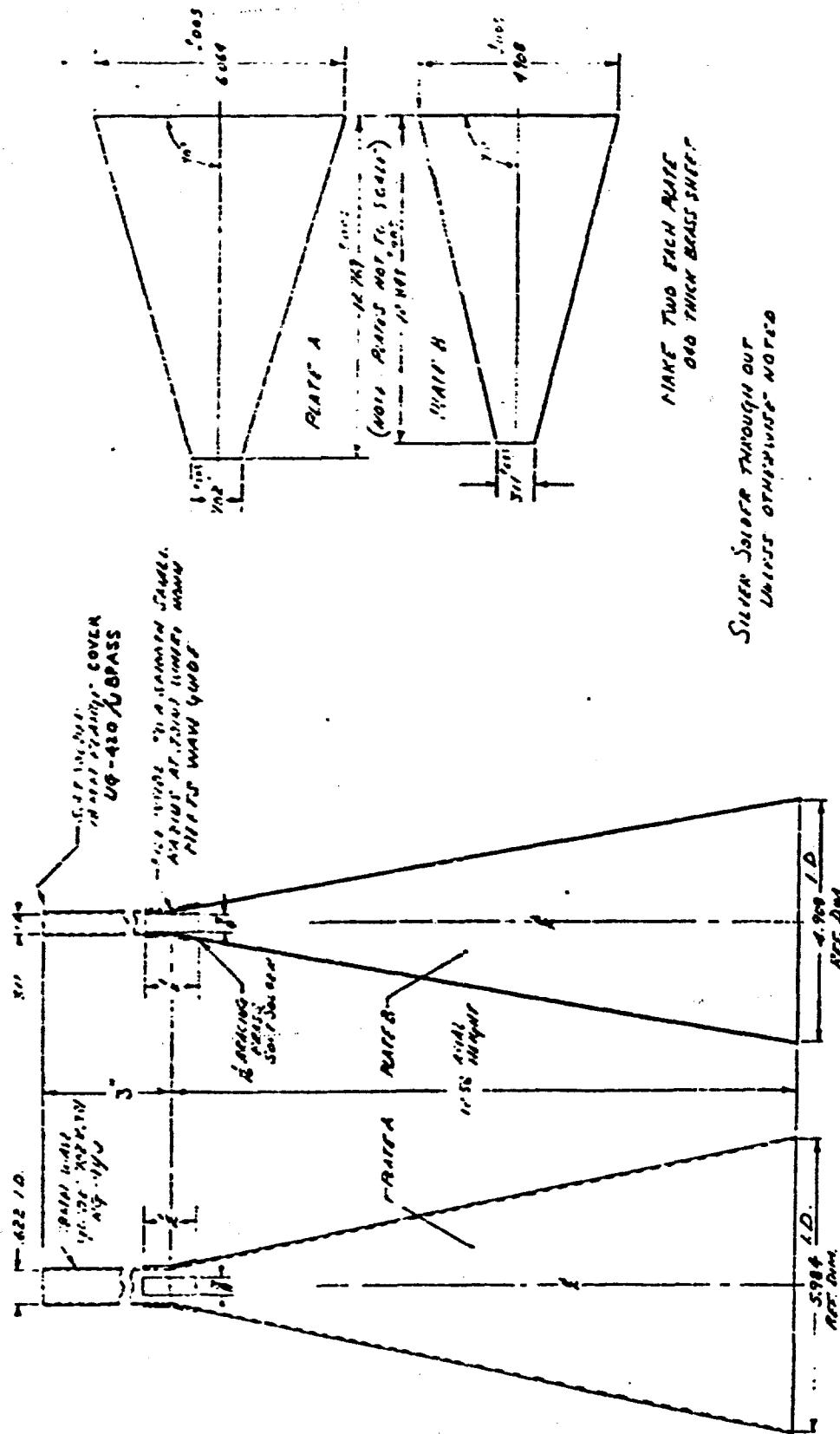


Fig. A-9. 18-mm-band gain-standard horn (11.66-2.42 cm)

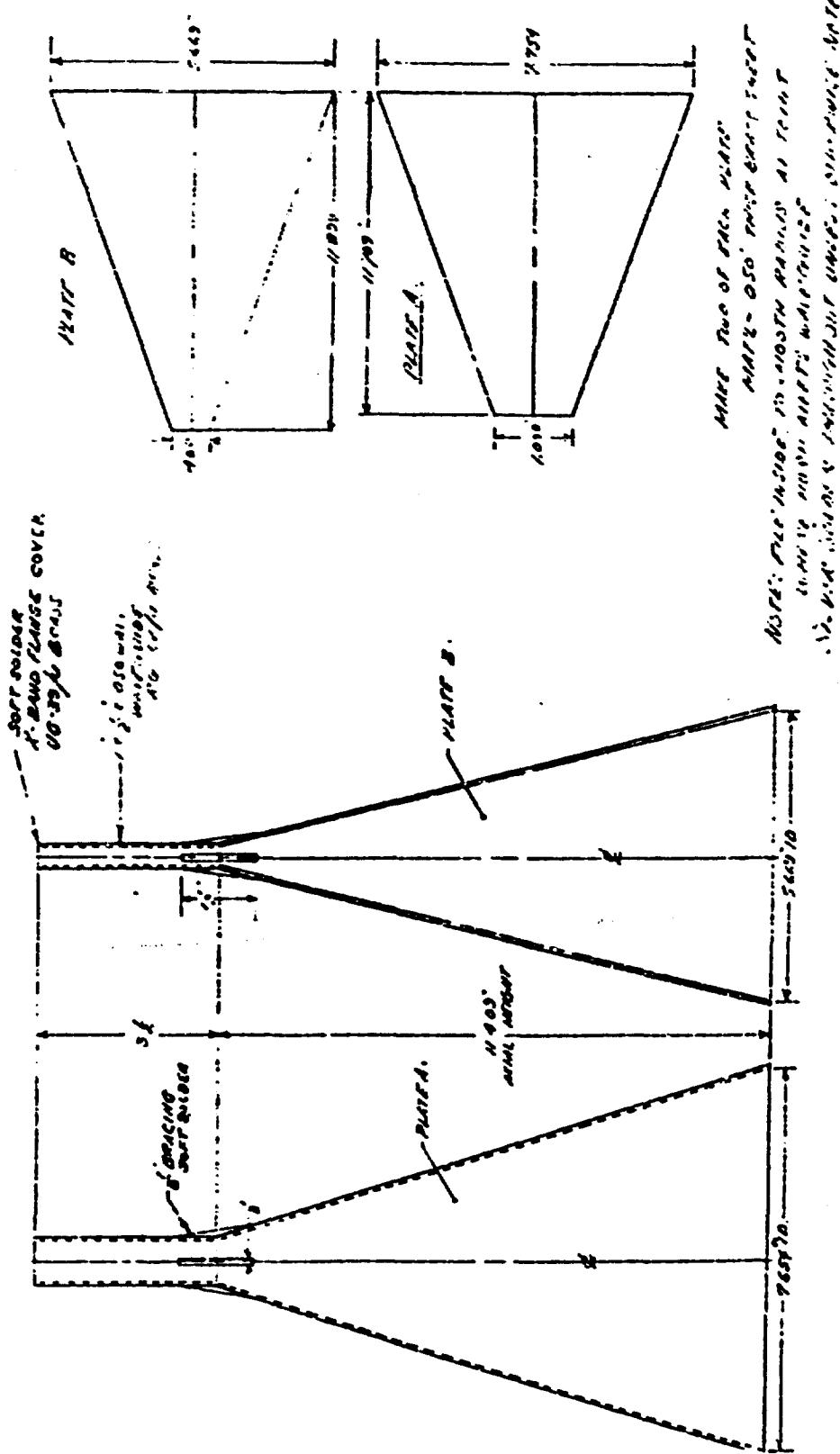


Fig. A-10. 3.2-cm-band gain-standard horn (2.42-3.70 cm)

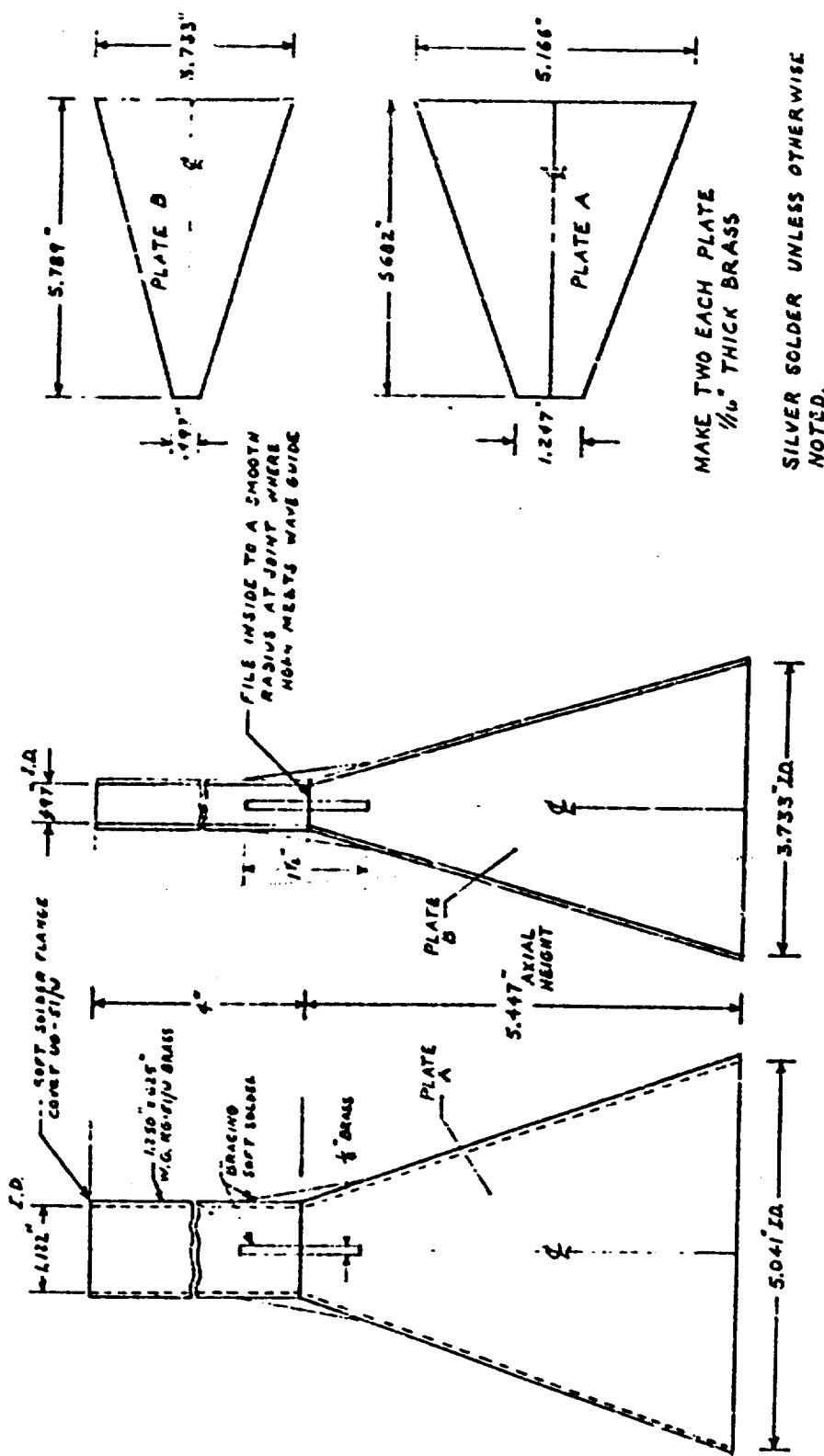


Fig. A.11. 3.95-cm-band gain-standard horn (3.0-4.30 cm)

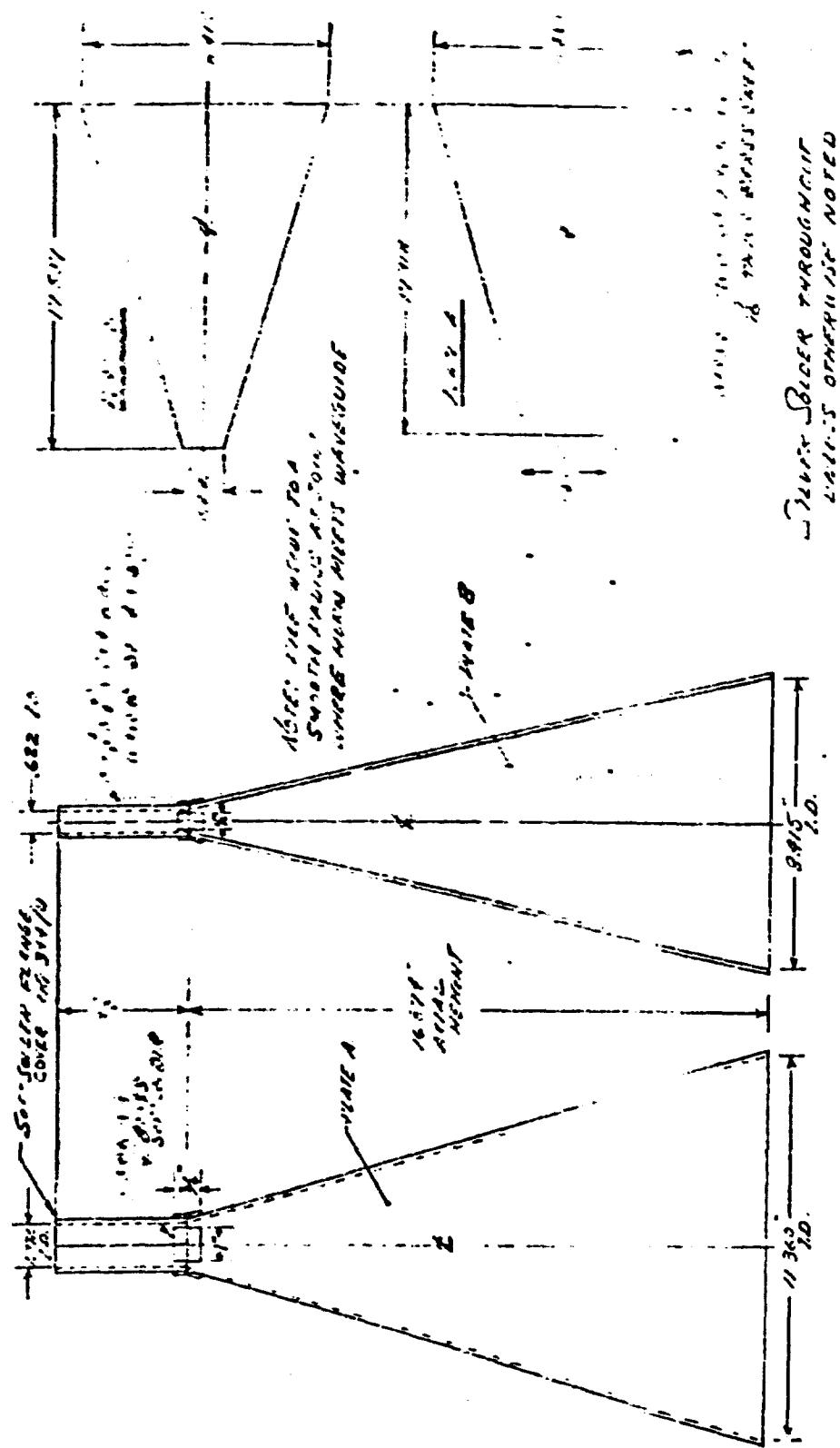


Fig. A-12. 4.75-cm-band gain-standard horn (3.60-5.20 cm)

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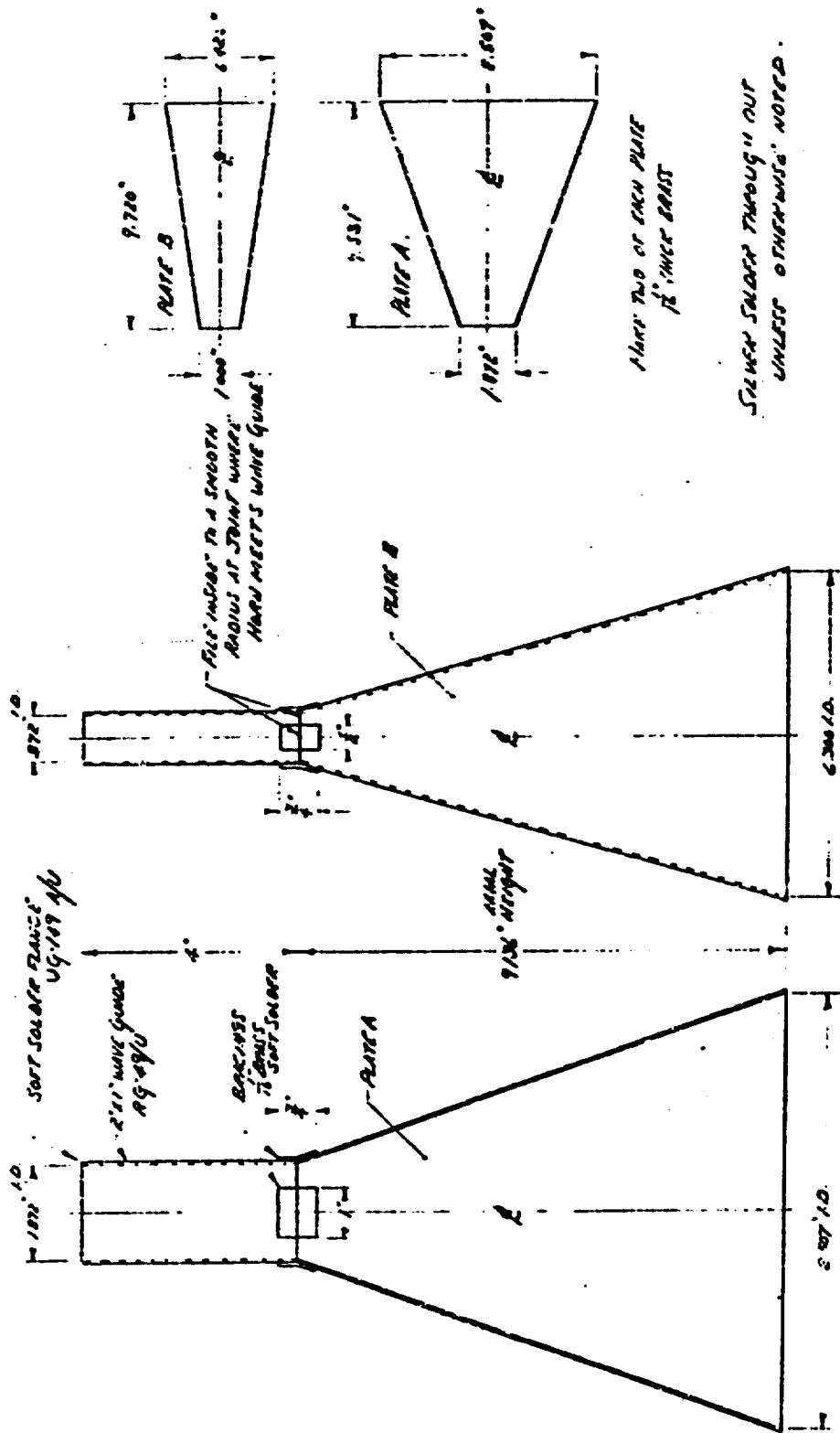


Fig. A-13. 6-cm-band gain-standard horn (5.10-7.60 cm)

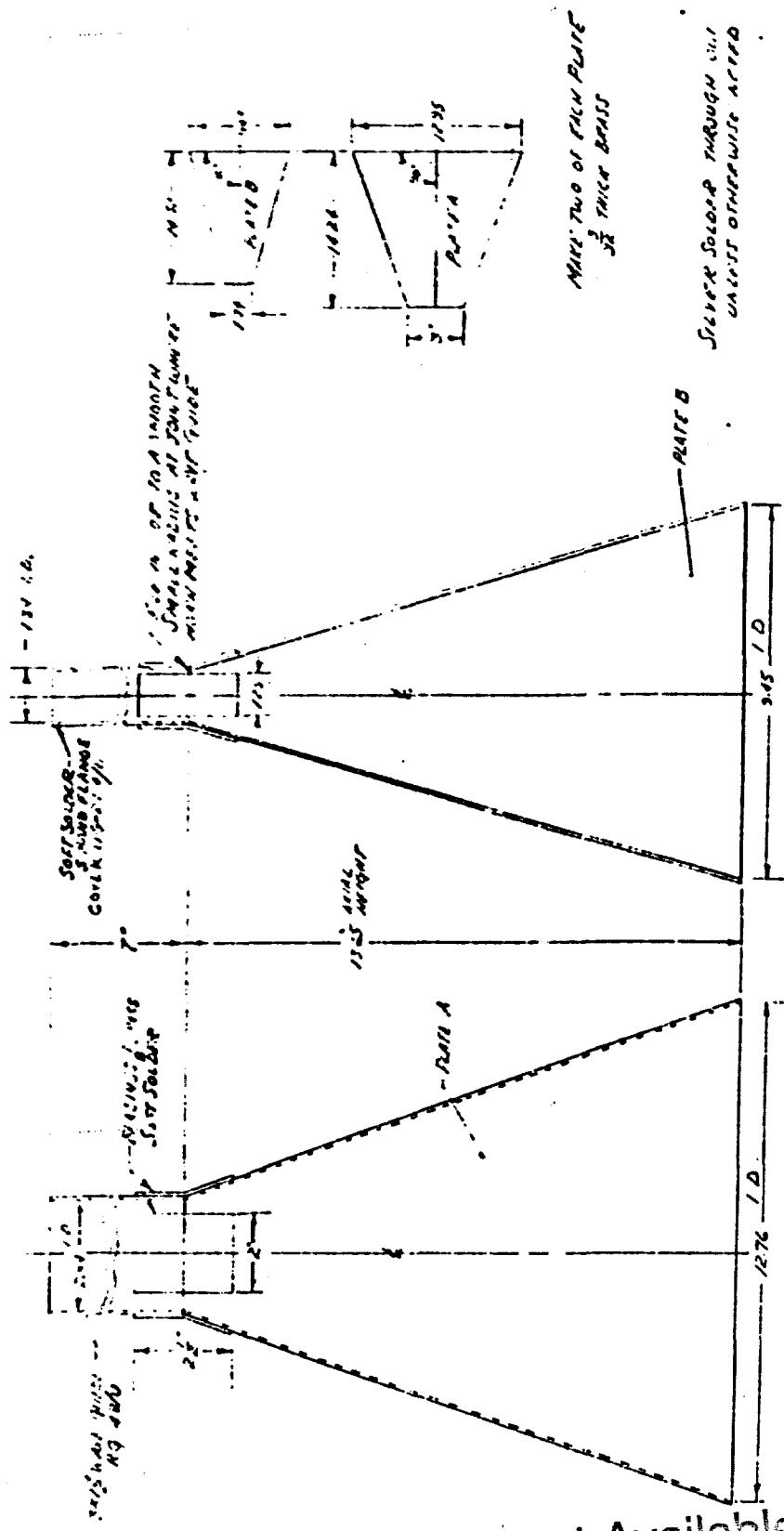
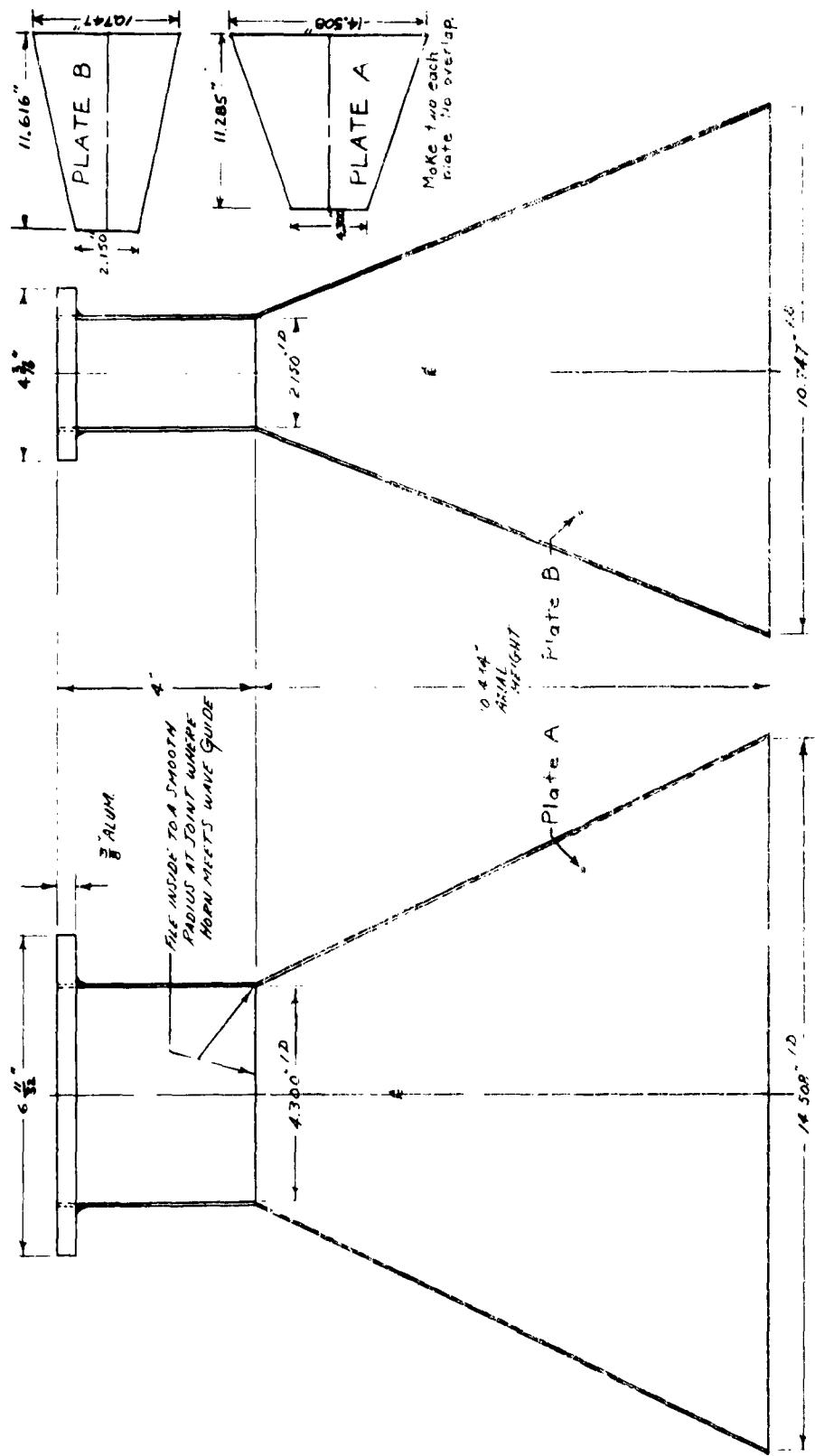


Fig. A-14. 10-cm-band gain-standard horn (7.60-11.5 cm)

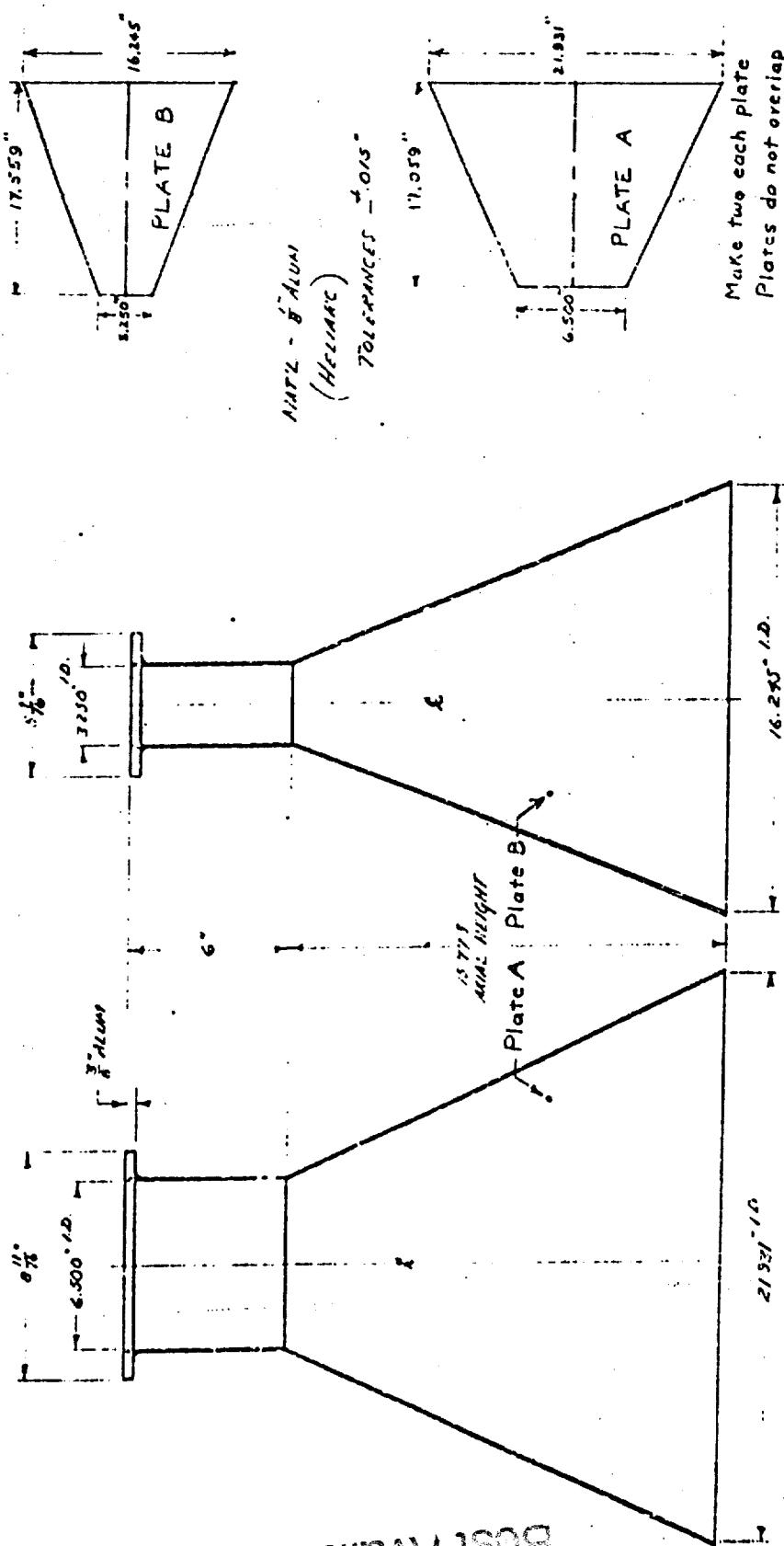
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15-cm-band gain-standard horn (11.5-17.6 cm)

4.452" ALUM (HELIARC
TOLERANCE + .010")

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NOTE: FILE NARROW TO A SMOOTH RADUS
AT JOINT WHERE WORN PLATES MEET GROOVE

Fig. A-16. 23-cm-band gain-standard horn (17.6-26.5 cm)

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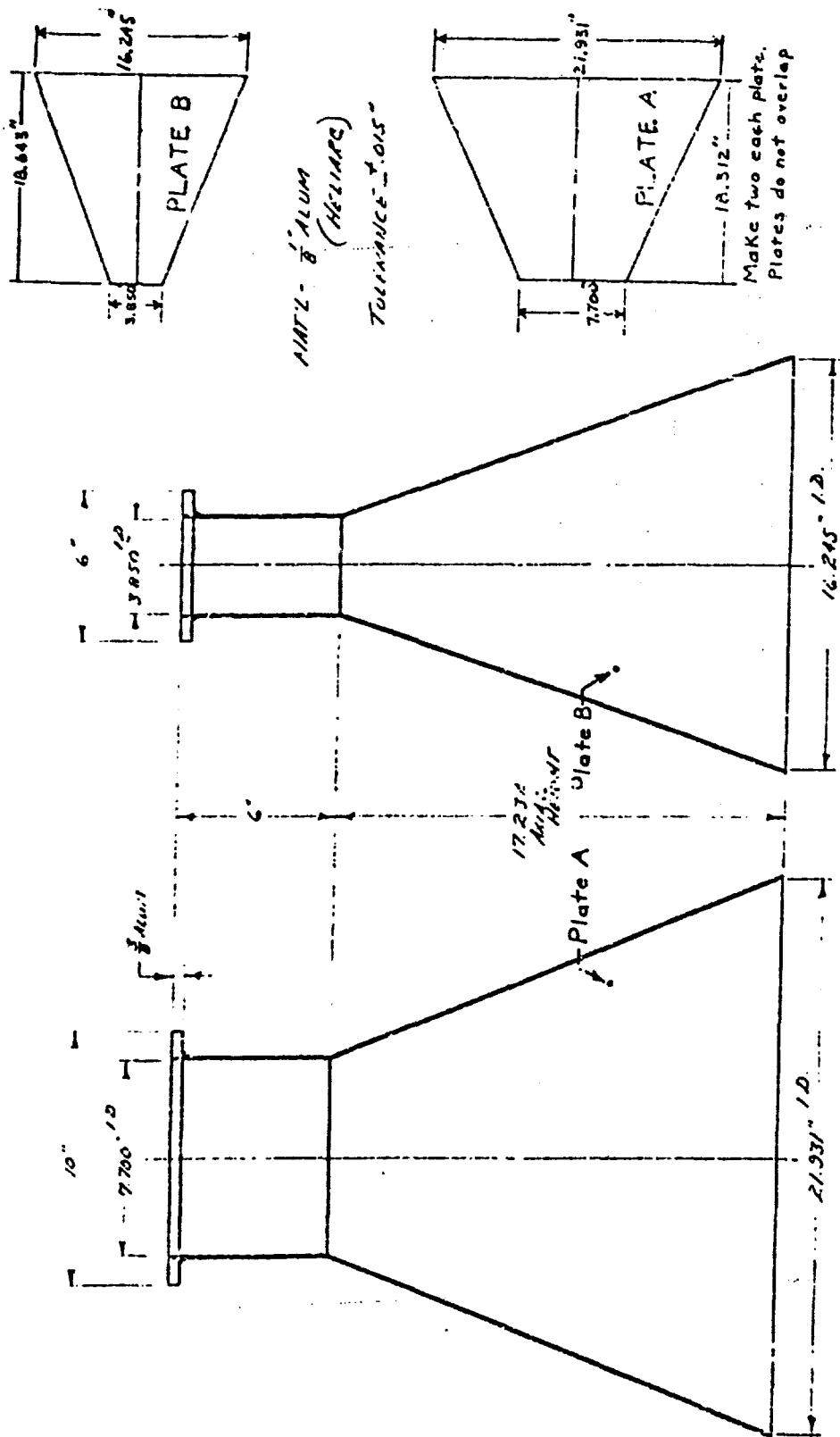


Fig. A-17. 30-cm-band gain-standard horn (26.0-31.5 cm)

Note: this mode to a smooth radius at joint where wave meets guide.

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